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THE ENVIRONMENTAL IMPACTS OF PRODUCTION AND USE OF ENERGY

PART IV – COMPARATIVE ASSESSMENT OF THE ENVIRONMENTAL IMPACTS OF ENERGY SOURCES

PHASE III – ASSESSMENT OF TOOLS AND METHODS FOR INCORPORATING THE ENVIRONMENTAL FACTOR INTO ENERGY PLANNING AND DECISION-MAKING

June 1986

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C O N T E N T S

PREFACE

One of the tasks assigned to the Governing Council of the United Nations Environment Programme by the Genaral Assembly of the United Nations in its resolution 2997 (XXVII) of 15 December 1972, is to:

> "Keep under review the world environmental situation in order to ensure that emerging environmental problems of wide international significance receive appropriate and adequate consideration".

The United Nations Environment Programme has undertaken a number of indepth reviews of the environmental aspects of production and use of all sources of energy. Three studies have been carried out. The first one, dealing with the environmental impacts of production, transport, processing and use of fossil fuels. The second study deals with the environmental impacts of nuclear energy. The third study deals the environmental aspects of renewable sources of energy.

The fourth study deals with the Comparative Assessment on the Environmental impacts of the Production and Use of Energy. A panel of expert met in Munich in 1980 to discuss the background papers prepared by my predecessor Dr. Essam El-Hinnawi on the Comparative Assessments of the Environmental Impacts of the Protection and Use of Energy. The panel gave a long list of contents and a few recommendations. In order to cope with these recommendations and tackle effectively this very challenging subject the study was divided into a number of phases.

Phase I serves the purpose of being a source of up-dated information of comparative data on the environmental impact of the production and use of energy sources. However, these data alone could not be used to undertake a complete comparative assessment. This is because the environmental impacts of the different energy sources vary in magnitude, duration, nature and even in space, i.e., in the place of their occurance. For this reason it was necessary a undertake a separate study on the cost/benefit analysis of the environmental impacts of energy sources.

Phase II of the comparative assessment consisted thus of a study prepared by the Technical Research Centre of Finland on the cost/-benefit analysis of the environmental impacts of energy sources. Its purpose was to take a further step in demonstrating and analysing the, methods of comparing the costs and the benefits of the environmental impacts of energy sources. The study was discussed in an Expert Group Meeting held in Helsinki in 1984. Finalized and published in 1985. (UNEP.ERS-15-85).

The two studies assisted also in pointing out the serious gaps in information on the environmental impacts of the production and use of energy and the limitations of the cost/benefit analysis approach. They also numerated the obstacles in generalizing the data obtained in phase I on the emissions, residuals and health hazards of energy sources and in undertaking a complete cost/benefit analysis using the methods presented in phase II. An extremely important result of both studies was that the environmental impacts of the production and use of energy is very much site specific. It was also felt that in spite of the guidance the two studies offer to decision-makers, planners and scientists there still exists a need of developing that "yard stick" which the planners and decision makers can use to incorporate the environmental factor into their final planning and decision-making processes. Hence was the justification to undertake a study on this subject.

The original purpose of the present study, i.e., phase III of the comparative assessment was to assess and develop tools and methods for incorporating the environmental factor into energy planning and decision making process. However, as a gesture of circumspection UNEP's Programme Management decided to start first with a study on the assessment and to concentrate in a separate phase on the development and use of these tools and methods. Hence was this study the purpose of which was to review the available tools and methods for incorporating the environmental factor into energy planning and decision making processes particularly in connexion with the electric power systems. This was agreed upon and emphasized in Helsinki Expert Group Meeting. The Group also emphasized the importance of developing the tools and methods needed.

The present study was supported by the Ministry of Environment of Finland, UNEP and the Technical Research Centre of Finland and undertaken by the Technical Research Centre of Finland. The research team consisted of

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One important point was emphasized in this report, viz, it is feasible to develop, apart from what is available, several models and computer codes which would be of considerable help to planners and decision makers for incorporating the environmental factor into energy decision-making process. One important model would be the energy-environment optimization model (chapter V). It has the advantage of reserving to each country its right of stipulating its own environmental laws and regulations in accordance with its environmental, social, economic and technical conditions and of having, at the same time, an international flexibility.

It is hoped that the discussions and the examples of the tools and methods available to incorporate the environmental factor into energy planning and decision making process included in this report would be of assistance to decision-makers, and planners and of interest to scientists to stimulate their efforts to undertake further relevant studies.

It is also hoped that UNEP would be able to continue its support in order to complete the study on the Comparative Assessment and to develop and use the tools needed for imcorporating the environmental factor in energy planning and decision making process as phase IV of the comparative assessment study. This would be of utmost importance to planners and decision-makers, and will comply with the recommendations of Helsinki Expert Group Meeting.

I wish to acknowledge the support and encouragement of Dr. Mustafa Tolba the Executive Director of UNEP and Dr. Olli Ojala, Director, Ministry of Environment of Finland in the course of undertaking this study.

Nairobi, Dec. 1985

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CHAPTER I

EXECUTIVE SUMMARY AND CONCLUSIONS

A. INTRODUCTION

Planning of electric generation systems is an important field of economic planning with long traditions and well developed and sophisticated methods. Environmental considerations have entered the electric generation planning problems most clearly in many hydropower projects, but in particular in recent years increasingly in the planning of fossil fueled and nuclear power plants. There are, however, no readily available methods in common use for including other environmental effects as there are for the traditional generating system planning.

It is the purpose of this report to describe the present situation in the field of incorporating the environmental factor energy in energy system planning process and to give some guidance on how to proceed with planning eletric power ststens in the absence of applicable well developed methods.

The basic difficulties facing the attempt to include the environmental factor in the energy planning process are no more due to lacking methodology than they are due to lacking quantitative information on the environmental impacts and to the difficulties inherent in comparing the environmental impacts of very different natures to economic values.

The disparity in the level of applicability of available methods and in the amount of quantitative knowledge may easily lead the decision-maker to ignore in practice the environmental factor, when they are not as well understood as the technico-economic factors. On the other hand, the same lack of knowledge makes the decision-maker reluctant of effectively withstanding the political pressures and requesting additional expenditures to protect the enviroment from damages or risks.

The only way out of this dilemma is to improve the quantitative understanding of the environmental effects and the capabilities of the decision-makers and planners to compare quantitatively all the different consequences of alternative ways of action. This means that one should aim at performing a comprehensive analysis of costs and benefits of each alternatie and using the results of these analyses to assess comparatively the alternatives. The decision-making on an important project should thus include data collection, risk assessment and management which in turn include environmental impact analysis, a cost/benefit analysis and finally a comparison of scenarios. The result will be the real comparative assessment (Fig. 1.1. Environment line). Whether each of these steps should be performed using some traditionel methods is by no means equally obvious.

The United Nations Environment Programme (UNEP) has collected information on the methods of cost/benefit analysis and comparative assessment as well as data on the environmental impacts of the production and use of energy fources (see e.g. Ahmad, 1981, 1982, 1983, ElMahgary 1984, VTT, 1985a, UNEP, 1985b). Similar work has been performed by several other international and national organizations (OECD, 1979, 1980, 1981, 1983, House, 1981, Ratick, 1983, Friedrich, 1984). University groups and research laboratories have developed more sophisticated methods, based often on large mathematical models (Dennis, 1978, Foell et al., 1981, Abilock and Fishbone, 1979, Schrattenholzer, 1981), but there have commonly been difficulties in attemps to apply them in practical planning situations.

B. PLANNING OF THE ELECTRIC POWER SYSTEM

The basic requirement for electric power system is that it can assure with high reliability the supply of electricity under all foreseeable situations. The planning situation is made complicated by the fact that construction of power plants and transmission systems takes typically 5 - 10 years from the date the decision on the construction is made to the date the corresponding power is available. Thus the future needs of generating capacity has to be estimated years in advance - a task that has turned out to be impossible to perform with good accuracy even in highly industrialized countries with mature economies and energy systems and long traditions in collecting statistics and preparing economic forecasts.

The second starting point in power system planning is the economic aspects. The total costs of producing electricity should be kept as low as possible. The long planning horizon and rapidly changing fuel prices make costs comparisons even more difficult than the estimation of the need of capacity.

Estimation of the need for generating capacity and of the consumption of electricity is usually not included in the planning models, but separately done on basis of national economic forecasts, pasts trends, estimated technological development, known or forecasted large industrial investements, etc. Also the national energy policy has naturally its bearing on the need of eletricity. (Fig. 1.1. Energy line).

The uncertainties of the demand and economical forecastas lead often to the need of analyzing several alternative cases (scenarios). On comparing the results of these several analyses one should search for a programme for expanding the generating system thatc an without excessive economic penalities be adjusted to each of the scenarios.

The traditional planning methods for electric generation expansion concentrates on estimating the right amount and timing of capacity additions together with choosing the most economic plant types for the expansion. In recent years environmental considerations have been included in some countries in planning systems, but, in general, not at a level or a stage comparable in importance with economic factors.

A systematic approach to energy planning includes a number of steps, such as

- defining the goals and wider objectives of the plan,
- determining the approach to be taken,

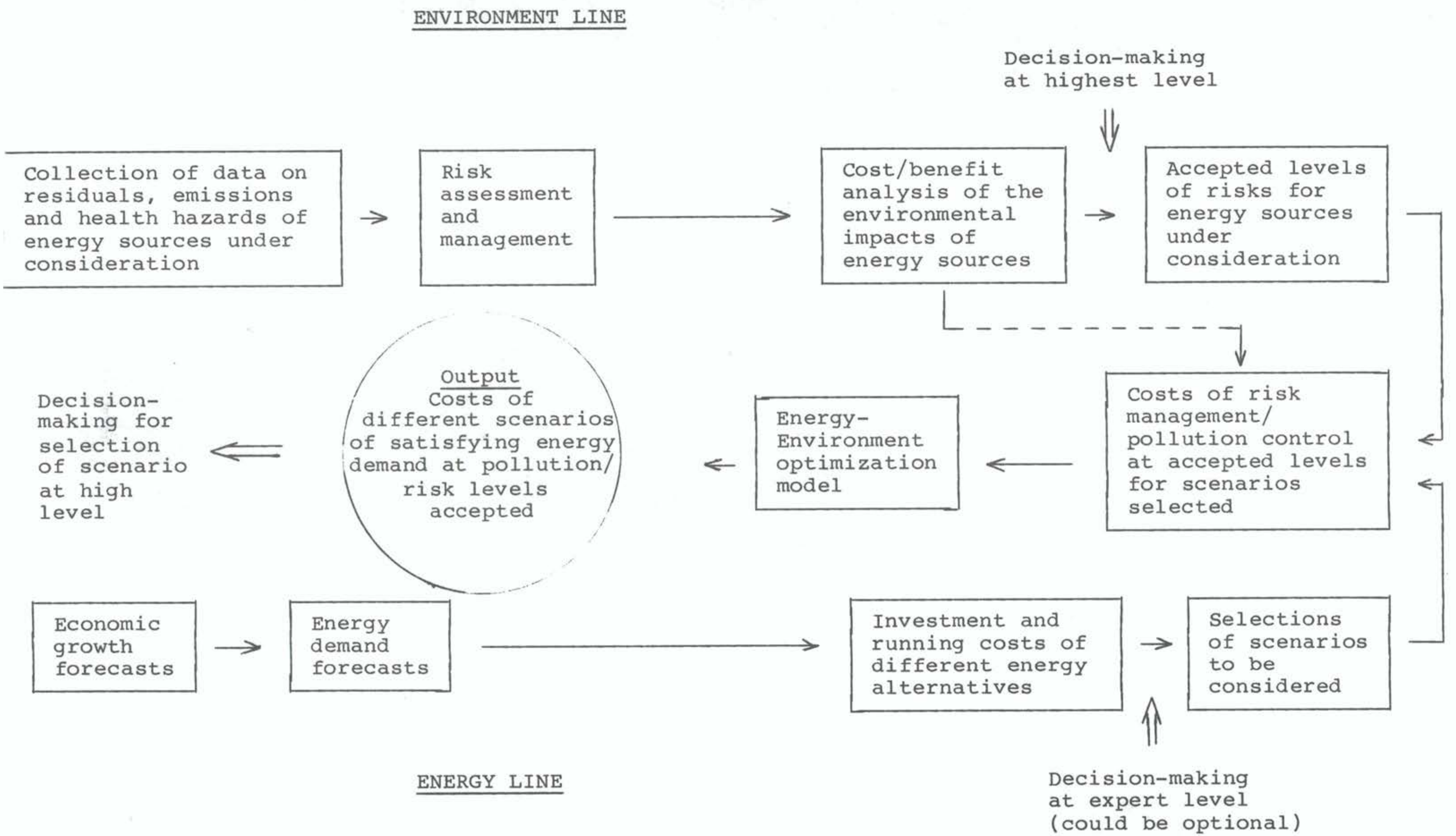

Fig. 1.1 Merging Energy & Environment lines into the Energy Environment Optimization Model.

Source: ElMahgary 1986

- identifying the information required from the planning process,
- choosing the analyzing process,
- conductiong the analysis,
- presentation of the results to decision-makers, and
- preparing the energy plan.

The methods used in electric generation planning include various optimization methods (most notably dynamic and linear programming), simulation of demand and availability variations and supplementary models or methods used in economic calculations and many other subtasks of the analysis. Some models use straightforward optimization without simulation, some others are pure simulation models. A combination of both techniques is also used.

The main role of simulation is to take into account short term variations in the load, including seasonal, weekly, daily and in some cases even shorter term variations although, these are usually taken care of by spinning reserve capacity and peaking units, whose planning can be kept as a separate shorter term planning task. Ind addition to the variations in the load, also the availability of each unit in the generating system is taken into account in typical simulation programs as this has an equally important effect on the ability to balance the generation and the load. Pure simulation models can be used in detailed analysis of the reliability and operational costs of a small number of alternative expansion plans.

Optimization is used in general to find the least total cost alternative to satisfy a given need for electricity. Pure optimization models cannot take fully into account the ariations in load and availability. Therefore they are most commonly used in preliminary screening of the alternatives and in very long term planning. Neither of these tasks requires detailed studies of reliability.

In a comprehensive model like WASP (IAEA, 1984) or EGEAS (EPRI, 1982) a combination of simulation and optimization is used. Such models require extensive computer calculations and are thus relatively expensive to use. A large amount of experience has been obtained on the use of these models proving their usefulness in performing the tasks they have been built to perform. A complete simulation of the load variations is usually considered to be too wasteful to be included in the optimization calcualtions. Therefore, only part of the variations is simulated, while the rapid daily variations are included throuugh the use of load duration functions.

The planning of expansion in the hydropower capacity differs in many respects from the planning of other power plants. One important difference is that every hydropower project has its own unique charactristics with respect to the size of the plant, variations of availability during the year and from year to year, and with respect to the construction cost of the plant. Possibly the largest differences are, however, due to the dam and reservoir projects very often connected to the construction of the plant and the various further effects related to the water management. The planning of hydroprojects is therefore in most cases done separately from the rest of electric system planning and included in the latter as predeterminded additions to the generating capacity. The planning of hydroprojects with its multitude of positive and negative consequences to the society and environment forms a traditional field of application for cost-benefit analysis. It is not considered further in this report.

In most planning models of electric generating systems the environmental consideration have been either completely excluded or they have been included on an incomplete level. In many optimizing models a number of environmental factors is calculated and listed as output, but they do not affect the optimization itself. In some others, mainly linear programming models, environmental constraints could be set up or some measure of environmental factor be could included in the objective function. In many cases only the total emitted amounts of certain pollutants were taken into acount, other environmental consequences were left outside the model system.

C. METHODS USED IN ENVIRONMENTAL ASSESSMENT OF ENERGY SYSTEMS

The first step of all environmental assessments is to collect the avialable data on all significant environmental consequences of the project alternatives being considered (first two blocks of environment line Fig. 1.1). In order that the conclusions and results of the comparison based on this data would be meaningful, the selection of the environmental impacts to be considered must be based only on the significance of the impacts, not on the quality of the data available. The handling of purely qualitative "low-quality" data is certainly difficult in the later steps of the analysis, but this should never be accepted as the reason for leaving the impact out of comparisons.

A badly known, or only qualitatively described, impact, when well enough understood, might reverse the whole conclusion. Thus it may be more useful to concentrate on improving the knowledge on this point than to perform a sophisticated model analysis of the impacts which are better understood but have less consequences. Similar considerations apply to collecting quantitative data: the importance of the data should always dominate over the accuracy and ease by which the data can be obtained.

The proces of collecting and reporting the environmental consequences of a project is commonly known as environmental impact analysis or assessment (EIA) which is a part of the risk assessment process. An EIA is an integral part of licencing procedures of major energy and industrial facilities in many countries. The form and content of EIA depends greatly on the project in focus, but many common aspects can be discerned in the methodology and composition of environmental assessments.

Proceeding beyond collecting and reporting a description of the various environental consequences of a projet one may try to rank several alternatives with the help of a comparative assesment. In a classical comparative assessment the differences in the consequences of the alternatives are obtained, but usually no attempt is made to produce a single value of merit, in monetary or any otehr units. Thus it is common that the analyzing team leaves the final ranking or choice of the best option to decision-makers without giving any clear recommendations.

A comparative assessment should always be defined in such a way that all the major direct and indirect differences resulting from the alternative decision will be taken into account. For more details on the definition of comparative assessment please refer to phase I of this study (UNEP, 1985a). If domestically produced fuels are used in the power plants being compared, the implicants of fuel production should in some way be taken into account. This includes, of course, equally the impacts on local economy and employment and of course practical to rest on a separate analysis of the mining project e.g., an a include the effects from the conclusions of this analysis. When the analysis is performed, e.g., by a country importing all its coal and oil, it might appear prudent to exclude the effects of coal mining from the comparison of coal and oil fired power plants. Those effects should be taken into account by the exporting country in deciding on the price of coal and, indeed, on the willingness to export coal at all.

An example of comparative assessments have been performed in the OECD's Compass Project (OECD, 1983) discussed briefly in this report. In extensive comparative assessments very large amounts of information are often collected and manipulated. Several large computer implemented models have been developed to aid in this work. Perhaps the most comprehensive model is the Strategic Environmental Protection Agency (EPA) of the U.S.A. to assess the impact of EPA policies on the economy and the environment (House, 1977). Another large model system developed by the University of Wisconsin and International Institute for Applied. System Analysis (Dennis, 1978, Foell, 1981) is described in chapter IV of this report.

One principal limitation of the classical comparative assessment is that usually no clear recommendations are given for the action to be taken. This would require accounting of all the costs and all the benefits of on a common scale and adding them up to give a quantitative ranking of the projects. If benefits are taken positive and costs negative, a positive sum would indicate a worthwhile project and a negative sum a project to be rejected. From several scenarios the one with largest positive sum should be chosen (or possible the one with largest sum compared to total investments included in the project). Analysis of this type is called cost-benefit analysis (CBA). Methods and uses of CBA have been discussed in several publications of UNEP (Ahmad, 1981, 1982, 1983, ElMahgary 1984, UNEP, 1985b and others.

Although CBA may appear the ultimate and best guide for decision-making on large projects, it is beset with many difficulties. First of all the fully quantitative nature of CBA requires that all factors being taken into account should be given quantitatively an in the same units. This leads in practice either to neglecting effects that are too difficult to quantify or to performing more or less arbitrary quantifications of these effects. When the results are then summarized in extreme cases by one number, the results may be dominated by the arbitrary and subjective choices done by the analyst. When the analyst indicates properly this weakness of the analysis, the decision-maker may be unwilling to give any value to the CBA. The situation is, of course, worse, if uncertainties and subjectiveness of the analysis are left unstated.

Various methods have been developed for involving the decision-maker in the definition of the difficult-to-define coefficients in order to get rid of the subjective judgement of the analyst and to replace it by the supposedly more relevant opinions of the decision-maker.

Commonly these methods are, however, not sufficiently transparent to allow intelligent use of them by anybody except (possibly) modeling experts. In other words, they can provide only very limited support for the decision- maker.

From the above discussion of CBA, it follows that a complete and fully quantitative CAB is a goal worth the pursuit, though currently seems very difficult to achieve. After all, any method of making a choice between several alternatives involves an implied relative valuation of the alternatives. An explicit, openly discussed relative valuation should, in general, be better than an implied, intuitive valuation by one or few decision-makers.

There are some more fundamental limitations in the basic idea of a complete CBA, e.g., that there should exist exactly one best solution to a planning problem. This is, however, hardly the normal situation, because there are no unique values that could be used to indicate, which society is best. Even this fundamental limitation should sometimes be remembered, although it often can be ignored in the practical analysis. The largest practical risks are, however, related to the use of an incomplete or badly performed CBA as a replacement of a more transparent approach to decision-making.

On the other hand CBA would be extremely useful if its purpose will not be limited to comparing in monetary terms the costs and benefits but rather to provide the decision-makers with the adequate information of the costs and benefits of the different alternatives at different risk levels. These are the basic data needed in making decisions on pollution control and accepted risk levels (fourth block in environmental line fig. 1.1).

In some comparison the comprehensiveness of CBA is either unnecessary or not easy to achieve. A more limited approach called cost-effectiveness analysis can be used instead. In cost-effectiveness analysis the least-cost method of reaching the objective is searched for or the unit cost of, e.g., reducing the total emissions of SO_2 is calculated for various alternatives. The cost-effectiveness analysis is a natural part of any CBA, indeed several cost-effectiveness analyses are usually performed during an extensive CBA.

One further step which logically follows the CBA is to computerize decision-making through the use of mathematical optimization techniques. In principle they start from an approach of CBA and use some optimization procedure to look for the best solution in the sense of the CBA. Multigoal optimization methods, which require interactive usage by the modeler or decision-maker are often applied. If the approach is not carefully developed and applied, practical considerations might force the modeler to accept a rough and much aggregated model for the description of the problem. This seems to be a serious limitation of the method. In this case it would be very difficult even for an expert to judge, how meaningful were the results.

If, however a decision could be reached on the accepted level of pollution/risk, using the above mentioned information, then the rest is a straightforward optimization process in which the environmental factor could be incorporated Fig. 1.1.

D. FEW RECOMMENDATIONS FOR INTEGRATING THE ENVIRONMENTAL FACTORS INTO POWER PLANNING SYSTEMS

In the previous sections and in more details in the rest of this report, methods that have been used in electric generation system planning and environmental considerations, have been described and commented upon. The variability of the planning problems and resources available to planning make the presentation of generally applicable recommendations on methods to use very difficult. Therefore the recomemdations to be presented below are not very specific or concrete. They also may not apply to all generating systems.

1. Use transparent methods. This may be the most umportant point, often repeated, but equally often neglected in practice. Transparency means that the user of the analysis understands precisely the connectiion between the important starting points and the results of the analysis.

   Only through transparency can the user judge properly the role of uncertain or subjective inputs to the analysis. The extent of these uncertainties and subjective inputs makes the transparency more central in environmental decision-making than in many other planning problems.

2. Be comprehensive. The whole idea of including the environmental factor in energy planning is to avoid one-sided, biased decisions. Comprehensiveness means that no important factors are to be neglected. If the effort that can be put to the analysis is limited, leave out detailed studies of factors of less than crucial importance.

3. Be as quantitative as possible (but do not spend effort on unimportant details). Performing a quantitative analysis, whenever data of sufficient reliability and accuracy is available helps greatly the decision-making stage, because a large number of factors can thus be summarized by a small number of quantitative results of analysis. Even the requirement of transparency can be relaxed, if both data and methods of analysis are generally accepted as reliable.

   Some quantitative analysis should be applied also to less understood factors, here the transparency of the analysis is crucial.

4. Be open about uncertainties. Uncertainties may be due to statistical fluctuations, attempts to forecast the future or imperfect knowledge of facts. Technically the reason for uncertainty makes usually little difference. For statistical fluctuations the probability distribution is, however, often known making possible the calculation of expectation values and statistical variations of the results of the analysis. In other cases some typical situatiosn or perhaps extreme cases can be analyzed to indicate the extent of uncertainty. Uncertainties about the future are often taken care of through analysis of several scenarios, sensitivity analysis or probabilistic functions (UNEP 1985a).

5. Be open about subjectivity. Objectivity should, of course, be aimed at, whenever possible, but the environmental problems seldom allow avoiding all subjectivity. All significat subjective choises should be indicated and justified, commonly presented alternative views should also be presented together with arguments for and against these views. The analysis should either be presented for all justified views or it should be transparent enough to allow the decision-maker to deduce the consequence of various points of view.

Choice of methodology

The five recommendations presented above do not contain any direct comments on the basic choice of the analyzing method to be used in some particular situation. They have, however, clear implications on the methodology.

For maximum transparency and optimal use of analyzing resources, the methods should not be unnecessarily complicated. The level of useful quantitative accuracy is limited by the most significant unresolvable uncertainties in the data base, although it is, of course, worthwhile to calculate all the well-known factors with the full accuracy available without extra effort.

In considerations of expansion planning of large or even intermediate generating systems it is usually advisable to use at some stage one of the models described in the chapter II or some similar model. Presently none of these models supports a comprehensive enough analysis of environmental factors, although many of them perform very useful subtasks for the environmental analysis. For more limited problems it is not always necessary to use any models to study the need, timing or economy of the power plant.

With the present level of availability of computing resources and supporting soft-ware, it is practically invariably advisable to collect the information needed in environmental analysis to some computerized data base. Depending on the continuity and level of the environmental planning the data base may be a large continuously maintained one on a large main-frame computer system or a simple partly temporary data base on a personal computer. In the former case the data base in used by large programs or computer models like the SEAS system mentioned above. In the latter case the whole analysis can perhaps be performed with the help of some commercial data base management and/or spreadsheet program.

Structurally complicated models are usually quite sensitive to changes in some input parameters like environmental impact coefficients and, in general, they are far from being transparent. The great uncertainties in much of the environmental impact data and the difficulties in obtaining unanimosity on the valuation of many environmental impacts make therefore such models quite unsuitable for practical environmental planning.

On the other hand a large energy system and comprehensive coverage of many environmental impacts may be most transparently represented by a large model, whose complexity is due to a large amount of detailed data. Indeed a detailed model with straightforward structure is often more transparent than a more compact model of the same system, because the latter is usually be based on more extensive aggregation. The aggregation of similar but nonidentical factors contains usually somewhat arbitrary choices, which make the model less objective and and often less transparent.

Combined models of the whole planning problem, including the requirements on the electricity supply system, economy and the environmental factors, can most easily be used in very long term planning and preliminary screening of the alternatives. At this level relatively straightforward models are generally used. Typical methods are simple bookkeeping models (basically of the structure of a spreadsheet) and perhaps most commonly linear programming. In these tasks linear programming is, in general, used in a way that might be called "simulation mode", because it is not really used to find a optimum, but rather to find just a feasible solution satisfying a very restrictive set of constraints.

In more detailed planning it appears from currently available models that a fully unified model including technical, economic and environmental considerations in sufficient detail is not practical. As is already the case with many generating system planning models, a number of environmental consequences can be calculated at this state. Similarly some environmental requirements can be included as constraints. Further, arrangements can be made for transferring the results of the above mentioned stage to the environmental data base for use in more comprehensive environmental analysis. This comprehensive analysis and the final choise of the best option should, in this approach, be made with the help of more transparent methods that allow giving proper weight to nonquantifiable and imprecisely known factors.

In case a detailed cost/benefit analysis and decisions on the accepted level of risk/pollution would be taken as anterior to the use of the model, the construction of energy-environment optimization models is advantageous and could be recommended. This reserves to each country the right of stipulating its own environmental laws and regulations in accordance with its environmental, social, economic and technical conditions - and at the same time gives the model an international flexibility. The purpose of the model will be to optimize the expansion and operation of the power system taking the environmental aspects into consideration. Hence it could be effectively used as a tool to incorporate the environmental factor into energy planning and decision making processes (Fig. 1.1).

CHAPTER II

PLANNING OF THE EXPANSION OF ELECTRIC SYSTEMS AND THE ENVIRONMENT ROLE

A. INTRODUCTION

Planning of the electric generation system cannot be carried out without taking into account the interactions of the power systems with the other energy systems and furthermore with the rest of economy. This chapter mainly concentrates on the description of the methods and models used in electric generation expansion planning. Few words are, also said on the general energy planning and on its interaction with power system planning. Furthermore a short description is given on the methods of how the environmental factors are taken into account in the electric generation planning models. More specific description of incorporating environmental factors in general energy system planning is given in the next chapter.

B. PROBLEMS ASSOCIATED WITH EXPANSION OF ELECTRIC POWER SYSTEMS

1. Power system planning as a part of general energy planning

The needs that an energy sypply system should meet are constantly changing, e.g., due to changes in prices of energy and materials, new technologies or environmental requirements. Therefore the effective energy planning is a dynamic process that is repeated periodically and is adjusted to changing conditions. It can be said (IAEA 1984) that

> The energy planning process is the systematic assembly and analysis of information about energy supply and demand and the presentation of this information to decision-makers who must choose an appropriate course of action

A systematic approach to energy planning includes a number of steps, such as

- defining the goals and wider objectives of the plan
- determining the approach to be taken
- identifying the information required from the planning process,
- choosing the analysis process,
- conducting the analysis
- presentation of the results to decision-makers and
- preparing the energy plan

The planning procedure and especially the analytical techniques and the methods of integrating the results of the different tasks may vary considerably depending on the needs of the country. However, there is a typical sequency of tasks that should be included in an energy analysis according to figure 2.1 (IAEA 1984)

The tasks are basically divided into the data base development and the integrated analysis. The database development is designed to assemble all the necessary information required to conduct an energy analysis. The integrated analysis is designed to structure the data into a consistent format that allows the planner to evaluate alternative scenarios. There is also a reviewing and evaluating procedure. Several iterations may be required as the results of the analysis become available.

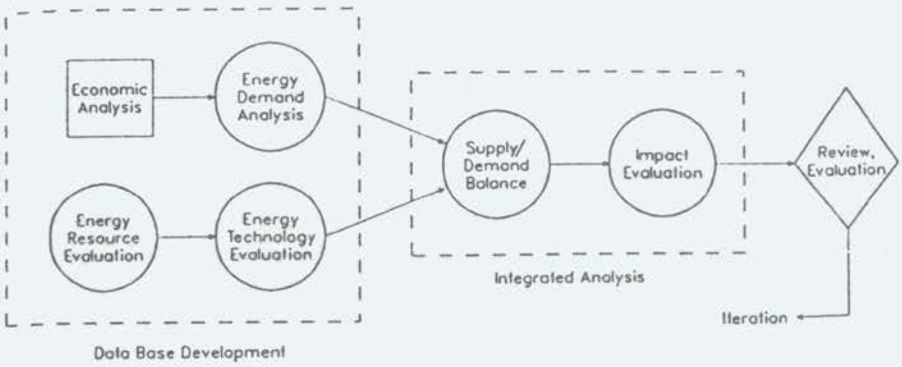

Fig. 2.1. Typical sequence of tasks in energy planning.
Source: IAEA (1984)

The methods and analytical tools used in electric system planning are similar to the above described methods used in energy planning. The main distinction is in the level of details. The main benefits of linking the two planning activities include

- avoiding duplication of effort,
- consistency of assumptions for important independent variables, and
- understanding the basis for the forecasts.

The main links between electric system planning and energy planning are

- demand forecasts, which should account for anticipated economic activity, population growth, and other driving forces for changes in electricity demand over time,
- financial analysis, especially financial constraints due to lack of capital,
- use of resources (fuel, labour) and
- environmental requirements.

From the methodological point of view there is no reason why the electric generation planning and the energy system planning cannot be conducted in a consistent way. The organizational requirements for implementing this are often the only obstacles.

2. Objectives of electric generation planning

The primary objective of electric generation planning is to meet adequately the demand for electric power at the minimum cost, taking into account the existing constraints, such as financial limits, domestic resource availability, and technical, environmental and political constraints. The time frame in generation planning is usually medium-term (5-10 years) or long-term (> 10 years) term. Only the planning of new peaking or cycling units can be done for less than 5 years' period.

The basic questions to be answered in the planning are (IAEA 1984) - what capacities (type and size) to install ?
- when is the proper time to incorporate them into the system ?
- where to locate them ?
- how to pick up the best combination among the different technologies at hand now and later on ?

Most models for long-term optimization of generating systems attempt to answer to at least three of these questions (where ? being the usual exception).

The development and expansion of power systems usually take place within a country or region where national or local energy policy provides wider objectives for the planning. These must be taken into account in the optimization of expansion and they may cause difficulties in the optimization. Also the power utility itself has other objectives than purely economic, such as
- long-term security of fuel supply
- utilization of domestic fuels and industry to ensure maintenance, spare parts, trained people etc.

The generation planning is also only a part of the whole power system planning including transmission and distribution system planning, financial analysis etc. Simultaneous consideration of the whole system is not possible. Therefore the long-term exansion planning of modern power systems is a step-by-step procedure, in which the planning is divided into two main phases according to the figure 2.2.

In the economic optimization phase the most economical expansion plan is searched according to the economic criteria selected for comparing the alternatives, while providing a satisfactory level of system reliability and continuity of supply and obeying other qualifiable constraints. In the detailed analysis phase the results of economic optimization are analysed and it is determined whether they are feasible from the standpoint of the system characteristics and the economic and financial situation of the region or country concerned. From this analysis the planner will check in more detail all potential constraints which were not explicitly taken into account in the previous phase.

In the following the main emphasis is made on methods and models used in the economic optimization of the expansion of power generating systems.

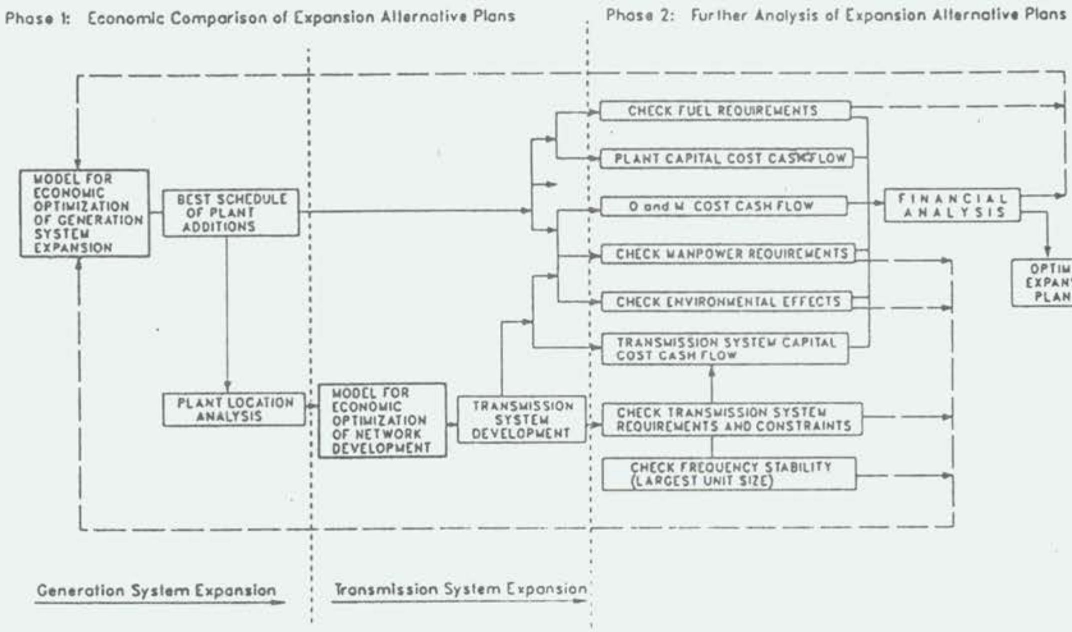

Fig. 2.2. Schematic representation of the planning process and consideration of constraints (IAEA, 1984).

C. OPTIMIZATION METHODS USED IN EXPANSION PLANNING

1. Optimization methods used in expansion planning

1.1 Definition of the expansion planning problem

a) Problem formulation

The optimization problem encountered in planning for electricity generation capacity expansion can be formulated as follows:

> The demand for electrical energy is assumed to be given for each year of the planning period. This demand must be covered so that the total cost of electricity generation is minimized within the possibilities and restrictions defined by the planner.
>
> The key elements in the problem are:
> - The set of possible expansion plans considered.
> - The set of restrictions and requirements to be met.
> - The optimization criterion used to select the optimal plan from the feasible plans.

The set of possible expansion plans is described by decisions variables. The restrictions and requirements define the feasible plans within the set of possible plans. The optimization criterion is usually the discounted total cost of electricity generation.

b) Desicion variables

The planner must first definite the length of the overall planning horizon. As the technical planning and constrution period for large hydroelectric or condensing power plants is 5-10 years, the planning horizon should be long, 20-30 years.

This in turn increases the data requirements and the volume of calculations to such an extend that, in practice the planner must often be content with shorter planning periods, say 15 years. In the following the planning horizon is denoted by T.

The different types of power plants that are candidates in the expansion plan are defined. The index i = 1,...,I distinguishes the type of plants Let us denote by $n_i(t)$ the number of plants of type i which are put into commercial operation at the beginning of year t. The unknowns $n_i(t)$, where i = 1,...,I, and t = 1,...,T, are the decision variables of the problem, and their totality forms the expansion plan.

A considerable amount of detailed technical analysis is required before the definition of the plant types to be considered in the expansion plan. It is not advisable to consider all theoretically possible alternatives within the optimization problem, since the data collection and the optimization would be too expensive. Instead, a realistic set of plant types must be chosen which includes base load units, variable load units and peaking units.

All hydropower projects are individual with their own cost and production characteristics. Of course, hydropower plants may be included among the plant type i, each plant as its own type. For each hydropower project $n_i(t)$ = 1 or 0, depending on whether the plant is built and put into operation in the year t or not.

However, hydropower plants have many definite advantages over other types of plants: independence of the raw energy market, no pollution, excellent reliability and load-following characteristics, and an energy source that can be stored in water reservoirs. For this reason hydro- projects are usually decided on an individual basis. They are taken as fixed additions to capacity in the overall optimization. Otherwise, the heavy investment costs, combined with high discount rates, could make hydroprojects appear economically infeasible. On the other hand, the profitability of some hydroprojects is so clear that it is not necessary to include these projects in an optimization process.

Many of the difficulties with the plant-capacity optimization problem are due to the fact that it is only possible to add an integral number or units of the capacity.

The decision variables $n_i(t)$ are positive integers (or zeros) and the capacity assumes discrete values. The optimization problem is a large discrete problem which is much more complicated than a similar problem with "continuous" decision variables. In certain long term studies it may be advantageous to approximate the problems so that all positive capacity values are allowed - not only the capacity values which consist of an integral number of plants.

In addition to the decision variables $n_i(t)$ concerning capacity additions, the planning problem includes decisions and corresponding decision variables that describe operation of the capacity; these variables describe operation by plan type, the use of raw energy, etc.

c) Restrictions and requirements

Resource requirements are the main source of the different restrictions that must be met by all feasible plans. In general, the following constraints can be given.

i. Demand must be met.
ii. Constraints on the amount of new capacity should meet certain limits.
iii. Raw energy constraints.
iv. Environmental constraints.
v. Technical requirements.

In a mathematical optimization problem the restrictions on decision variables $x_1,...,x_n$ are usually defined through constraint expressions

$$q_i(x_1,...,x_n) < 0, i = 1,...,n.$$

The expansion planning problem, however, is so complicated that it is usually impossible to write down all the constraints q_i and proceed in a formal, mathematical way. Instead, the values of different constrained variables are calculated and the solution either accepted or rejected on the basis of these values.

The motivation for capacity planning is the requirement that predicted demand must be met. Owing to the regular and random variations of the load, planned maintenance and random outages of the capacity, the form of the demand restriction becomes very complicated. It is not possible to require that capacity be sufficient to cover the load under all circumstances. Instead reliability requirements are defined for the solution.

Limited investment resources put limits on the amount of new capacity which can be built each year. Also, the planning and construction time for different types of unit define limits to the expansion plan.

The total amount of different types of raw energy available for electricity generation is limited. It may be hard to define exact numerical limits and apply these as constraints in the optimization. However, raw energy availability is certainly one of the most important problems in long term capacity planning.

Sulphur dioxide and other air-borne emissions are the most harmful pollutants from fossil-fuelled power plants. Nuclear energy also poses environmental problem. The environmental effects of fossil power and nuclear power are so different in nature that a common measure can hardly be defined.

d) Optimization criterion

The function to be minimized is the sum of discounted yearly costs for electricity generation. The costs include the following items:

For new plants only
- capital investment costs,
- salvage value of investment costs

For all plants
- raw energy costs
- fuel stock costs
- operation and maintenance costs

In general, every cost item must be included that is dependent on the expansion schedule. Capital investment costs for old plants are the same for all expansion plans, and thus they have no effect on optimization. These costs may therefore be omitted in expansion planning. However, this constant item can be included in the cost calculations.

The salvage value is calculated on the basis of plant lifetime. There is a further cost item which may be included in the cost function, viz. the cost of energy not made available. The difficulty with this elegant approach is the calculation of the normally nonlinear cost function. It is of cource totally independent of electricity production.

2. The central tasks in capacity optimization

a) General

In order to construct an electrical generation expansion plan, any approach must analyse certain central tasks. These tasks are treated in the following. In many cases an exact analysis of a subtask would lead to a very complicated and extensive mathematical study. Thus, in practice the planner must always choose approximations, and the alternative planning approaches and models differ from each other with respect to the approximations. There is no universal best method, rather a tradeoff between accuracy and the amount of study required, and between the amount of detail and flexibility.

d) Demand description

Let us consider any future year within the planning horizon. The time variable within the year is denoted by y, $0 \leq y \leq Y$ (=1 year), and the predicted demand is D(y).

When considering a future year, the demand is a random function, i.e. a function which varies stochastically. In capacity planning the demand is not usually treated formally as a random function - this would lead to a very complicated stochastic optimization problem. Instead different approximate methods to handle the variation of the demand are used.

A common approximation is to use the load duration function f(y) or actually its inverse function which is defined as follows:

> For any value of the load P $y = f^{-1}\{P\}$ gives the expected duration of time during which the demand $D(t) \geq P$.

So, if P is larger than the maximum of the demand, then $y = f^{-1}\{P\} = 0$ and if P is smaller than the minimum, then $y = f^{-1}\{P\} = Y$. As the load duration curve is formed, all information of the time order of the loads is lost. If the demand is described by a load duration curve, then it is impossible to treat any genuinely dynamic phenomena within the model. One compromise, which was used, e.g., in COMCELH model, is to first divide the year Y into subperiods Y_r, $r = 1, \ldots, R$ and then to describe the load with a duration curve within each subperiod (ElMahgary &Larsson 1976).

The continuous load duration curve may be further approximated by a step function or by a Fourier series expression (Jenkins et. al., 1977). Newer approximations are the representation of load duration curve with an analytic expression - a series of statistical cumulants fitted to the curve- (EPRI, 1982) or with a mixture of normals approximation (EPRI, 1985). These new methods improve essentially the calculation of production costs.

If the load duration curve is formed directly from the load values, then the area under the curve is the expected yearly energy consumption. Usually, the load duration curve is normalized so that the area under the curve equals 1 and the yearly energy and the shape of the load curve are predicted separately. The duration curve may be determined from historical data about load variations. If the same curve is used for planning work, the assumption is made that the pattern of load variations remains constant.

c) Generation capacity description

The level of detail in defining the generating capacity may vary. In general the thermal power plants are described by the following data:

i. Capacity of the plant
   - Maximum (net) capacity
   - Minimum capacity = minimum possible running level (0 is also possible).

ii. Heat rate
   - Heat rate valid at the minimum capacity level.
   - Heat rate valid between min. and max. capacities.

iii. Availability of the plant
- Scheduled maintenance requirements (days/year)
- Failure probability (forced outage rate) outside scheduled maintenance.

iv. Cost data
- Capital investment costs.
- Fuel costs.
- Fuel inventory costs.
- Operating and maintenance costs.

v. Plant life-time.

For hydropower stations the description depends very much on the accuracy required. Plant data typically include the following:

i. Power capacity
- Maximum and eventually minimum capacity.

ii. Energy capacity
- Energy available per period.
- Energy storage capacity of the reservoirs.

iii. Cost data
- Capital investment costs.
- Operating and maintenance costs.

iv. Plant life-time.

Energy and power capacities are subject to random variations from year to year. The calculations may be based on one sets of hydrological data only and this set then represents the average (expected) year. Varying hydrological conditions require their own sets of hydrological data with the probability for the occurrence of such a year.

d) The load models for the calculation of production costs and reliability

The production costs and the reliability must be determined for each year of the study and for each configuration considered for expansion.

The load is usually described by a load duration curve as explained above. Basically this load is allocated to capacity in a certain loading order. The order is either part of the input data or it is determined on the basis of the running production costs of the units. The plants (or units) are loaded one by one and the forced outage rate is taken into consideration in the process. Maintenance is scheduled during subperiods of the year.

The methods used in taking into account the forced outages of units have essential effects on the simulation time of production costs and the accuracy of the simulation and the reliability calculation. The aim is usually to form the equivalent load duration curve (ELDC) for each generating unit. This is done by computing the "equivalent demand" on a particular unit as a sum of customer demand and forced outages of previously loaded units. Basically, this calculation is done as a convolution of load curves and probabilistic forced outage curves. However, the straightforward convolution is time-consuming and more efficient methods are used especially in considering large systems. As was stated earlier, the methods can be based e.g. on Fourier series (WASP-program, Jenkins, et. al., 1977) or on the moments of equivalent load (EGEAS-program, EPRI, 1982) or on the mixture of normals approximation (EPRI, 1985).

The load model determines the anticipated energy generation for all plants during the year, and the reliability of the system.

e) Reliability calculations

When in the calculation of equivalent load duration curve (ELDC), all units with their outages are included, the expected unserved energy may be obtained as an area under the remaining curve, thus providing a measure of system reliability. The height of that same curve at the capacity point of the last unit in the loading order is the "Loss of Load Probability" (LOLP).

f) Running costs

The yearly production by each plant (or unit) in the generation determines the running costs in a straightforward way. Raw energy costs are the dominating item. In order to calculate these raw energy prices the energy efficiences of the units are needed. Operation and maintenance costs C_i for each unit i are calculated as the sum

$$C_i = C_{1i} + C_{2i}, \text{ where } C_{1i} = \alpha_{1i} E_i \text{ and } C_{2i} = \alpha_{2i} F_i .$$

E_i is the yearly energy production by the unit i as determined by the load model and α_{1i} is the time-dependent operation and maintenance costs, α_{2i} is a proportionality factor (constant) and F_i is the manned time, usually 1 year.

The only problems in production/running costs are thus to find adequate estimates for fuel prices and other cost parameters and to determine the loading of the units in all difficult situations where these costs are needed.

g) Investment costs

First, the total capital investment I_i for each new plant i is calculated. This includes the interest charges during construccion time. The discount rate ρ to be used in investment costs talculations is then decided upon. The third parameter needed the lifetime α_i of the plant. The most convenient way to calculate the investment costs is usually the following: for cach new plant the cost is the discounted investment minus the discounted salvage value at the end of the planning period. For dexample, if the costs at the beginning of a 20-year planning period are calculated and at the beginning of year 5 a new lant of type i, with a 25-year lifetime, is put into operation, the cost K_i is

$$K_i = (1+\rho)^{-4} I_i - (1+\rho)^{-20} \cdot \frac{1-(1+\rho)^{-9}}{1-(1+\rho)^{-25}} I_i$$

where the second term represents the salvage value.

In the determination of the discount rate the effect of inflation has to be subtracted from the nominal interest rate.

h) Algorithms for capacity planning optimization

The capacity optimization problem is a large mathematical optimization task with discrete variables. The planner must use his own judgement in reducing the number of alternative plans and configurations to be analysed in detail. In any case, simulation of the different configurations in each year - which is required in order to calculate the loading, reliability and running production costs - is a very time-consuming task even for a large computer.

Different kinds of algorithms can be used in actual optimization. In the following, a very short description of some commonly used methods is given.

- Pure simulation methods can be used, if the planner prespecifies the expansion program. The computing requirements for a production simulation program are usually much less than for capacity expansion program, and therefore the simulation models are more detailed. Often, the simulation models can use the load data also in chronological order, which makes possible to study also different time variations of production system.
- Linear Programming (LP) is often used for long term expansion planning. The LP model can be used quickly and efficiently as a screening tool to select a few planning alternatives for more detailed analysis. The basic limitation is its approximate modeling of system production cost and reliability, and in particular the fact that the capacity of a generating unit is a continuous function. The discrete nature of generating units can be treated by mixed integer linear programming, but the computational time and cost increase considerably.

- Dynamic Programming (DP) is based on enumerating all possible planning period and selecting minimum cost transitions from one year to the next. The main shortcoming is the large amount of of computation required to analyze a large number of planning alternatives. DP-method is used e.g., in WASP- program.
- Year-to year optimization is based on considering only one year at a time. Although the computing requirements are much smaller than those required for a global optimization, the approach tends to introduce less capital intensive generating units, which are not optimal in the long term. To improve the method, some look-ahead algorithms have been developed, where the operational cost estimate for the look-ahead period typically (5-10 years) is utilized.
- The Generalized Benders' (GB) decomposition analysis option is a sophisticated algorithm based on iterative use of simplex (LP) algorithm for a master capacity decision problem and on the solution of a set of detailed nonlinear probabilistic production costing subproblems (EPRI 1982). Although installed capacity is represented by a continuous variable, the GB option unlike LP, is capable of resolving unit sizes in the production costing subproblems and accounting for the impact of unit size on system operating costs and reliability.

D. REVIEW OF SELECTED MODELS FOR CAPACITY PLANNING

This section is based on the comparison made in the EPRI Report (EPRI, 1982) where some main features of several models were introduced. The models introduced were:

The next six models are compared in more detail in table 2.2, and the EGEAS Model is reviewed in table 2.3. The latter model includes several alternative solution methods, together with these compared in the table.

- WASP: a dynamic programming model with probabilistic production costing development by Jenkins and Joy.
- OPTGEN: A dynamic programming model with deterministic production costing developed by Lee.
- University of Massachusetts Model: A mixed-integer linear programming model developed by Noonan and Giglio.
- MIT Model: An economic-environmental system planning package developed by the MIT Energy Laboratory.
- PUPS: a screening curve model developed by Lee and Dechamps, capable of treating new energy technology generation.
- MNI-GRETA: An optimal control model (MNI) and a Monte Carlo simulation model (GRETA) used by EDF.
- GMP: A Generation Mix Planning package which is an adaptation of WASP by Southern Company Services, Inc.

MODEL ATTRIBUTE	University of Mass.	WASP	OPTGEN	MIT	EDF	PUPS
Solution Method	Mixed integer Linear Programming	Forward and Backward Dynamic Programming	Forward and Backward Dynamic Programming	Linear Programming	Optimal control and Decomposition	Screening Curves
Problem Size	Limited	Limited	Limited	Limited	Limited	Unlimited
Availability of Suboptimal Plans	NO	Yes up to 100	Yes up to 100	NO	No	NO
Reliability Estimate	Approximate Distribution	Probabilistic ELDC	Approx. Distribution	Reserve margin	LDC, outages Deterministic	Chronological Simulation Model
Variable Cost Est.	Deterministic outages	Probabilistic ELDC	Loading Trapezoid Deterministic outages	User Specified Capacity factors	LCD, determi-ministic outages	Chronological simulation
End Effects Accounting	YES	NO	YES	NO	NO	YES
Environmental Effects	NO	NO	NO	YES	NO	NO
Hydro Alternatives	NO	NO	NO	YES	NO	NO
Storage Alternatives	YES	YES	NO	YES	NO	NO
Unconventional Alternatives	NO	NO	NO	NO	NO	YES
Interconnection	NO	NO	NO	NO	NO	NO
Computational Burden	Moderate	High	Moderate	Moderate	High	Low

Table 2.1 Comparison of six models (EPRI, 1982)

The next six models are compared in more detail in the table 2.2, and the EGEAS Model is reviewed in the table 2.3. The latter model includes several alternative solution methods, and these are compared in the table.

MODEL ATTRIBUTE	GMP	WAGP	OGP	O/U	RPI Model	BNL-REFS
Solution Method	Dynamic Programming	Screening & Branch & Boumd	Myopic one future period opt.	Pespecified Mix	LP	LP
Problem Size	Limited	Limited	Limited	Limited	Limited	Limited
Availability of Suboptimal Plans	YES	NO	NO	NO	No	NO
Reliability Estimate	LOLP Probabilistic	Options, deterministic or probabilistic LOLP	LOLP Probabilistic	Unserved Energy Probabilistic	*	NONE
Variable Cost	Probabilistic Production Costing	Deterministic or Probabilistic Production Costing	System Operation simulation	Probabilistic Production Costing	Sequential Multiple Objective Technique	Exogenous
End Effects Accounting	YES	*	NO	YES	*	NO
Financial Considerations	Engineering Revenue Requirements	YES, Constraints	Yes, post plan selection interface with financial model	YES, detailed	NO	NO
Environmental Effects	NO	YES, Constraints	Reporting only	YES, objective function	YES, objective function	YES, Constraints
Siting	NO	NO	NO	NO	NO	YES
Hydro Alt.	NO	YES	YES	*	YES *	YES
Storage Alt.	YES	*	YES	*	NO *	YES
Thermal Alt.	YES	YES	YES	YES	YES	YES
Unconventional	NO	NO	NO	NO	NO	NO
Interconnection	NO	*	NO	NO *	NO *	NO *
Computational Burden	Moderate to High	Moderate to High	Moderato to Low	Moderate	Moderate	Moderate

* insufficient information available

Table 2.2 More detailed comparison of other six models (EPRI, 1982)

MODEL ATTRIBUTE	SCREENING CURVES	LINEAR PROGRAM	GENERALIZED BENDERS' D.	DYNAMIC PROGRAM	PRESPECIFIED PATHWAY
Solution Method	Screening Curves	LP (Simplex)	Mathematical Decomposition	Dynamic Programming	Stand Alone Probabilistic Production Costing
Problem Size	Unlimited	Limited	Limited	Limited	-
Availability of Suboptimal Plans	YES	NO	YES	YES	-
Reliability Estimate	Deterministic LDC	Reserve Margin and Determ. LDC	Probabilistic Production Simulation	Probabilistic Production Simulation	Probabilistic Production Simulation
Variable Cost	Deterministic LDC	Exogenously specified	Probabilistic Production Simulation	Probabilistic Production Simulation	Probabilistic Production Simulation
End Effects	NO	YES	YES	YES	YES
Financial Considerations	NO	Interface Preprocessors and Constraints	Interface Preproces-sors and Constraints	Interface Postprocessor	Interface Postprocessor
Environmental Effects	NO	YES, Constraints	Postprocessor Only	Postprocessor Only	Postprocessor Only
Siting	NO	YES	NO	NO	NO
Hydro Alt.	NO	YES but poor	YES good	YES Excellent	YES Excellent
Storage Alt.	NO	YES but poor	YES good	YES excellent	YES excellent
Thermal Alt.	YES	YES	YES	YES	YES
Unconventional Alt.	NO	NO execpt prespecified	YES	YES	YES
Interconnection	NO	NO	NO	YES	YES
Computational Burden	Low	Moderate to Low	Moderate	Moderate to High	Low

Table 2.3 Comparison of the different analysis option of the EGEAS model (EPRI, 1982)

- WAGP: An automatic expansion program developed by Westinghouse which utilizes a combination of screening and branch and bound logics to select the optimum capacity expansion plan.

- OGP: An Optimized Generation Planning program developed by General Electric utilizing operation models together with a myopic one-future-period (year) optimization technique repeated to evaluate a 20-year capacity expansion plan.

- O/U: A model developed by Decision Focus, Inc. for EPRI with the objective of studying costs and benefits of Over/Under capacity in Electric Power Systems Planning.

- The RPI model: An energy appraisal model developed at Rensselaer Polytechnic Institue which utilizes an LP formulation to study the effects of environmental constraints on the optimal capacity expansion plan.

- The BNL: REFS Model: A siting LP model developed by Brookhaven National Laboratory to allocate capacity to counties based on environmental impacts, transmission, and coal transportation costs.

The report (EPRI, 1982) gives also a detailed description of the EGEAS model, which is a very comprehensive model having several alternative solution algorithms depending on the needs of the user.

Table 2.1 gives a short comparison of the first six models basing on the review by Lee et al. (1978). From these models it can be noted that WASP, Wien Automatic System Planning package, is widely used in different countries. It was originally developed by Tennessee Valley Authority and the Oak Ridge National Laboratory of the USA to meet the needs of the International Atomic Energy Agency (IAEA), Vienna, and it is available from IAEA to member states. The model is described by IAEA (IAEA, 1984).

E. CONSIDERATION OF ENVIRONMENTAL EFFECTS IN THE EXPANSION PLANNING MODELS

As it was pointed out in the section B.2, the problem of the expansion of generation system is very large, and the economic optimization phase cannot include all detailed restrictions. This is true also for environmental effects, and usually they are considered in the detailed analysis phase (see figure 2.2) after the economic optimization phase.

Some models described in the section D can, however, treat also environmental effects. Usually, the environmental factors are included in the constraints, and the models check that the given limits are not exceeded. In some models they are also included in the objective function, but this kind of optimization can be carried out only in a very rough level, because the economic consequenses of the environmental effects cannot be defined unanimously.

Usually, the environmental effects are included only in the linear programming models, which, on the other hand, are less accurate in the production costing considerations. Consequently this kind of models are suitable for the rough selection of few alternatives to more detailed analysis.

A basic assumption in the linear programming approach is that emissions and other consequences are a linear function of plant capacity and energy output. The constraints include, e.g., in the EGEAS model the actual limits on total emissions within a site (or area) and within the total system. These are in the form of total mass of SO_2 or particulates allowed, amount of water consumed, amount of heat output and the total area of land used. Fuel data pertaining to SO_2 (and particulates) content and emission factor as well as removal efficiences for various pollution abatement technologies should be provided by the user.

CHAPTER III

CURRENT METHODS OF INCORPORATING THE ENVIRONMENTAL FACTOR IN ENERGY DECISION MAKING PROCESS.

A. INTRODUCTION

Like other activities of man, energy use implies different environmental impacts. Production of energy may cause pollutant emissions, exposure of living organisms as well as inanimate environment, and corresponding health impacts and material damages. Obtaining the fuels may result in depletion of natural resources, degradation of esthetic characters and changes in the socio-economic circumstances of local population.

Of the many environmental impacts associated with any energy technology, some are substantial and others small, some of short duration and others with long term effects, some might be adverse and other beneficial and they might occur in different geographic areas and might effect different communities in different ways (UNEP 1981). Many environmental concerns are recognized as falling in the unquantified category. This may be because the state of knowledge is insufficient or because the impact quantification is based almost entirely on value judgement. Further research may allow some of the unquantified impacts to enter the quantified category. 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 between the categories may take place as a function of time as suggested in Figure 3.1.

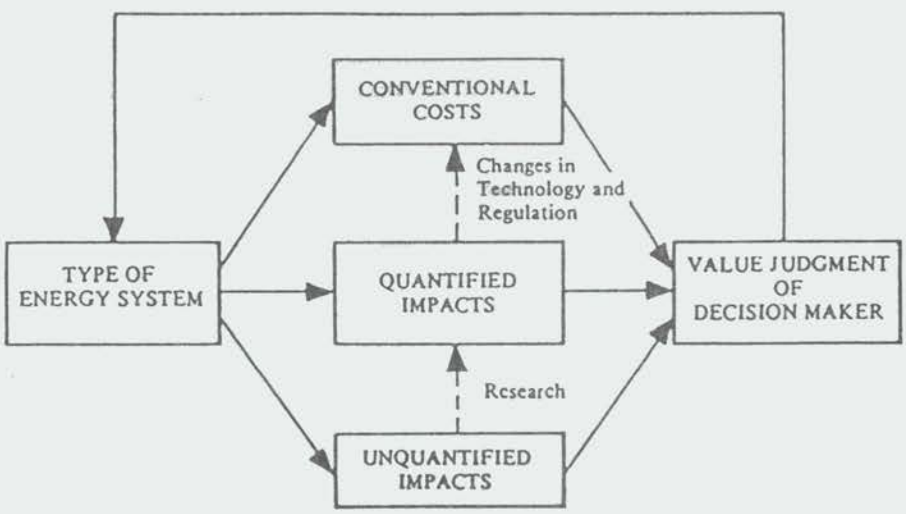

Figure 3.1. Factors in energy decision-making (Foell, 1979a).

Environmental effects of pollutants appear in many ways and thus different indicators can be used in evaluating them. For instance, air pollution concerns may be taken into consideration by focusing on the emissions, on the ambient quality of air, on the corresponding damages on man and nature, or even on the summarized value of the damages (Figure 3:.2). In general, more in-depth analysis of the causalities and using more than just one environmental indicator provides better support for planning and decision-making. The in-depth analysis is, however, also more burdensome. Whereas accounting of the emissions of a power plant is quite simple, the assessment of its impacts on the quality of air in the nearby city requires pathway analysis describing atmospheric transport and transformation of pollutants. Exposure analysis and dose/damage assessments are then needed to estimate the corresponding damages. Nevertheless, valuation of the heterogenous damages may turn out to be the most difficult task of a complete analysis.

Environmental effects are to be considered on the many levels of energy system planning and decision-making. The depth of the environmental analysis and the comprehensiveness of the overall energy-environmental evaluation must in each case be adapted according to the general goals of planning. There are, however, universal approaches which can support decision-making in a wide scope of enerxy-environmental problems. The methods frequently offered for including environmental effects in energy system planning and decision-making include:

- Environmental Impact Analysis,
- Comparative Assessment,
- Computer-implemented models of energy-environmental systems,
- Cost-Benefit Analysis,
- Optimization,
- Integrated analysis of energy-economic-environmental systems.

These methods which in many respects are overlapping will be discussed in the next sections.

B. ENVIRONMENTAL IMPACT ASSESSMENT

Identification and adequate description of environmental consequences of a proposed course of action is a prerequisite for proper inclusion of environmental concerns in planning and decision-making. An Environmental Impact Assessment (EIA), in which environmental impacts are systematically identified, described and, if possible, quantified, is therefore an essential part of the licensing procedure of major energy facilities in many countries (OECD, 1979a; OECD,

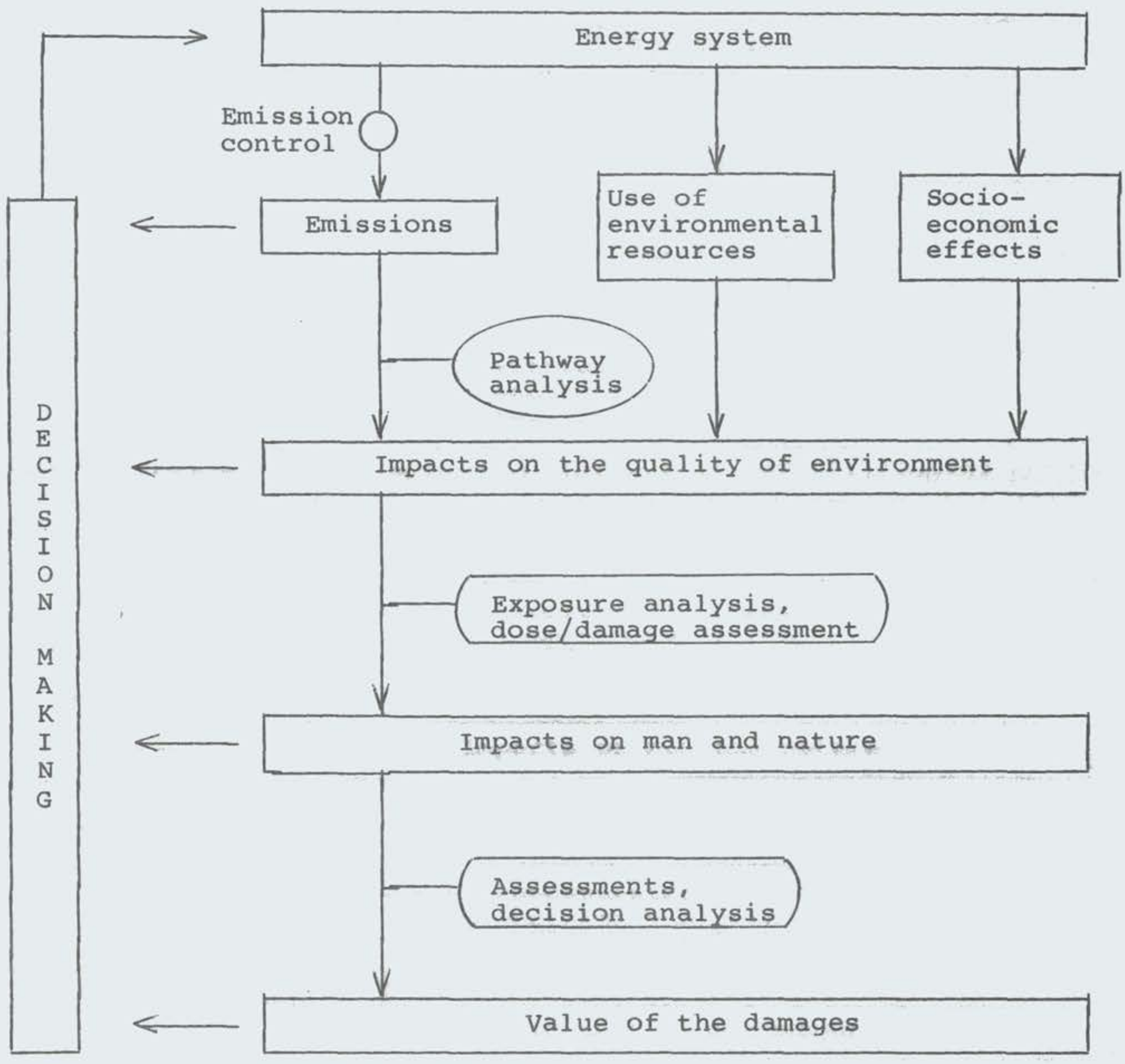

Fig. 3.2. Environmental effects in energy systems and methods used in analyzing and valuating them.

1980). The exact form and content of the EIA depends greatly on the project in focus. Nevertheless, common aspects can be discerned in the methodology as well as in the essential elements of environmental assessments of major projects (see e.g. Rau and Wooten, 1980).

Environmental impact assessment has to be based on a systematic identification of all the potential environmental consequences of a project on land, air, water, flora and fauna and human environment. Both direct and indirect effects should be considered. Various categorizations of impacts have been developed. For instance, in the United States, where an Environmental Impact Statement (EIS) is required for every proposal for major federal actions, the guidelines define the following range of environmental impacts to be surveyed (OECD, 1979b):

- Air - air quality; weather modification.
- Water - water quality, marine pollution, commercial fishery conservation and shellfish sanitation.
- Fish and Wildlife.
- Solid Waste.
- Noise.
- Radiation.
- Hazardous Substances: toxic materials; food additives and contamination of foodstuffs; pesticides; transportation and handling of hazardous materials.
- Energy Supply and Natural Resources Development: electric energy development, generation and transmission, and use; petroleum development, production, transmission, and use; natural gas development, production, transmission, and use; coal and minerals development, mining, conversion, processing, transport, and use; energy and natural resources conservation.
- Land Use and Management: land use changes, planning and regulation of land development; public land management.
- Protection of Environmentally Critical Areas: Floodplains, Wetlands, Beaches and Dunes, Unstable Soils, Steep Slopes, Aquifer Recharge Areas, etc.
- Land Use in Construction in Built-Up Areas.
- Density and Congestion Mitigation.
- Neighbourhood Character and Continuity.
- Impacts on Low-Income Populations.
- Historic, Architectural and Archeological Preservation.
- Soil and Plant Conservation and Hydrology.
- Outdoor Recreation.

Use of such checklists enumerating possible types of impacts certainly helps to ensure the coverage of the analysis. However, the danger is, that the increasing length and descriptive nature of the material makes it difficult to use the EIA as a real decision-making document. Care should therefore be used to identify the relevant impacts of the project under consideration.

The function of environmental impact assessment is to generate and make available information on the environmental consequences of a proposal. Environmentally beneficial as well as adverse effects should be considered. In a good EIA reference is made to the measures of avoiding or alleviating the adverse effects. EIA should also evaluate available options for the proposal under consideration, including the "without project" future situation.

The objective and preferably quantified assessment of each environmental impact is usually accompanied by an evaluation of their relative significance. Finally, the EIA should be concluded with recommendations on: "What to do?". Whilst in a given case it might be highly desirable from the environmental point of view for the project to be abandoned altogether, the environmental assessment should also consider the least detrimental alternative actions, and draw conclusions about the ways in which the project could be modified or regulated to reduce or safequard against adverse environmental impacts. In the case of planning authorizations, licenses, etc. the decision is frequently not simply "yes" or "no", but may be qualified by strict and detailed conditions. An important function of environmental impact assessment is giving clear guidance as to what such conditions might be (OECD, 1979b).

Performing an EIA does not manifestly ensure that adverse environmental impacts are averted or minimized. Nevertheless, environmental impact assessment of alternative courses of action is the first step for including environmental concerns in energy system planning and decision-making. It is a prerequisite for the more sophisticated considerations, like comparative assessment, cost-benefit analysis or optimization. In many cases systematical identification and adequate description and quantification of relevant environmental impacts by means of an EIA may be all what is needed for environmentally sound decision-making.

C. COMPARATIVE ASSESSMENT

Comparing available alternatives is a matter of course for everyone facing an important decision. In energy system analysis comparative assessment has been established to mean a special form of evaluation, in which several criteria are considered and the results are presented on the same plane to the decision-maker, or to the public. Ideally, the assessment can be divided to environmental impact analysis and environmental evaluation. The former is the task of the analyst. Environmental evaluation consists of ranking environmental impacts relative to each other, to the costs of abatement, or to the benefits of the activities, and should be left on the responsibility of the decision-maker. The analyst must, of course, be prepared to provide assistance for the decision-maker in weighting the list of impacts.

Three major studies covering the environmental aspects of production and use of fossil fuels, nuclear energy and renewable energy sources have been carried out by UNEP UNEP, 1981). This was followed by the comparative assessment study, which included data for comparative assessment (phase I, UNEP 1985a), cost benefit analysis (phase II UNEP 1985b) and the present study (phase III). Meanwhile, OECD has launched the COMPASS project studying the environmental effects of energy systems. The initial phase of COMPASS (OECD, 1983) discussed the methodology aspects of comparative assessment together with a review of some recent studies. Among the energy sectors, the first phase concentrated on space cooling and heating. The second phase of COMPASS compares the environmental impacts of generating electricity from different energy sources.

The methological issues and pitfalls of comparative assessment have been discussed by several authors (see e.g. Gleick and Holdren, 1981; House et al., 1981). Performing of fair environmental comparisons is not simple. The key issues determining the potential utility of a comparative assessment can be categorized in the following way:

- Transparency: For a comparative assessment to play a valuable and influential supportive role in the opinion-forming and the decision-making process, it must be transparent in its methods. Participants to the decision-making process must be able to discern the procedures by which data were transformed into the information from which conclusions are drawn. Assumptions must be made explicit, and the nature and degree of uncertainty identified (OECD, 1983).
- Bounding of the problem: The alternative ways of action should be considered in a consistent way and formulated as complete alternatives to each other.
- Coping with the impacts no matter how hard to quantify: Too often they are simply omitted, although they sometimes are the most important environmental consequences.
- Treating of the uncertainties: Uncertainties may reflect statistical fluctuations of a physical quantify (e.g. the impact of air pollutant emissions on local air quality); they may be a measure of imperfect knowledge of cause and effect (e.g. health impacts of a pollutant); or they may stem from an attempt to quantify the risk of an event not yet experienced (e.g. a major nuclear reactor accident or LNG tanker explosion). Uncertainties and the method or handling them need to be made explicit (UNEP 1985a).
- Objectivity: Many analyses tend to omit those classes of impacts that the analyst has decided are uninteresting, too hard to quantify or too likely to be "misinterpreted" (Gleick and Holdren, 1981). Furthermore, some studies seem to contain postulated health and environmental impacts that are based on speculative, unproven relationships and there is excessive reliance on arbitrary, subjective judgements in ranking the impacts relative to each other. Improving the objectivity leads, unfortunately, in many cases to very vague conclusions, even to the extent that their usefulness is in doubt.

Historically, most of the comparative assessments have concentrated on the health effects of different energy sources. The state-of-art of comparative risk assessment has been surveyed by Hamilton (1980; 1984). Several studies are presented in the proceedings of two recent symposia organized jointly by IAEA, UNEP and WHO (IAEA, 1982; 1984b).

Critical reviews (Paskievici, 1982) have indicated that only a few of the studies are independent. Most authors quote the results of previous studies or rest on a few primary sources. Furthermore, in many cases the analysts have had to rely on synthetically derived data. Individual items of data are rarely available in an appropriate form. Considerable manipulation, e.g. disaggregation, averaging and normalization, has been needed in order to use the information in the analysis.

A wide range of health and other environmental impacts were considered in the UNEP studies on production and use of energy (UNEP, 1981) and are updated in UNEP 1985(a) as well as in the COMPASS project of OECD. In the first COMPASS report (OECD, 1983), three regional case studies on space heating and cooling were reviewed. In general, the approach used in these studies was to compare the economic and environmental implications of selected scenarios. The coverage of environmental effects varied between the studies. No attempt was made to perform a unified valuation of the different effects. The principal goal of the studies was to describe to the decision-makers, and to the public, the complex of economic and environmental implications associated with each scenario. The choice was then left to them.

A most appropriate field for comparative assessment is in cases, where the problem is well-defined and the alternatives are few in number. This is the case, e.g, when a decision has to be made on the next major power plant for base-load electricity generation. Assuming the main alternatives to be coal, peat and nuclear power. Several studies and surveys have to be carried out on the implications of the alternatives. The impacts to be considered should include economics, balance of payment, direct and indirect employment effects, occupational and public health effects, short-range environmental effects on nature, landscape and materials as well as regional and global effects (e.g. acidification and effects on climate) (Kangas and Niininen, 1984). When the problem is limited in scope and well- bounded, the decision-makers can be considered to be quite capable of taking advantage of the full information obtainable from the comparative assessments. Summarizing valuation or subjective ranking of the impacts by the analysts could in this case be mainly confusing.

More sophisticated methods for comparative analysis of energy systems are reviewed in an overview by House et.al. (1981). These methods include the Delphi Technique, the Net Energy Analysis, the Indicator Analysis, the Comparison Matrices and the Multitechnology approach. Siskos and Hubert (1983) propose a multi-criteria method, which is based on fuzzy outranking relations and hence allows taking into account the uncertainties in the data and the vagueness of the preferences of the various interest groups. Although these novel methods have some advantages, even they would be affected by the poor quality of data available. Formal methods cannot either solve the trade-off problems of energy and environment. Therefore, it is not surprising that these methods have not gained any significant momentum in practice.

D. COMPUTER-IMPLEMENTED MODELS OF ENERGY-ENVIRONMENTAL SYSTEMS

Computer-implemented models are frequently offered for energy-environmental analysis. Computer models are claimed to be superior to qualitative assessments and "back of the envelope" calculations. Typical favorable arguments include:

1. Building of a formal model provides valuable insight and understanding of the system. The model points out the data necessary to be found and recorded.

2. Comprehensive, detailed and internally consistent analyses of complex systems can be performed only by computer models which can manipulate more information than the human mind and can keep track of many interrelationships at one time.

3. The use of computer models allows for more rigorous analyses because of the assumptions used in the model must be specified explicitly, completely and precisely; no ambiguities are possible.

4. The model construction and validation processes satisfy the basic requirements for a scientific method, because others can replicate the model analyses to check the results and can then perform their own analyses using their own assumptions.

5. When once implemented, a computer model provides the possibility of efficiently performing multiple "what if" analyses with a wide variety of different conditions and policies.

Computer-implemented energy-environmental models have, however, not gained either the acceptance or the success that many of their advocates feel they should have. Several reasons could be given for their limited success. In literature new designs are described rather than implemented. The model builders may claim that their model system evaluate energy-environmental interactions by means of an iterative process. Model builders also like to speak about considering of environmental effects even when their models are only accounting emissions. The contribution of models to decision-making is, of course, of minor importance when the results are either self-evident or too vague. Too often, the quality of documentation is poor. Most models are, in practice, not transferable and analyses cannot be checked.

A set of energy-environmental models consists usually of four main components: socio-economic input, which can be provided exogenously or by models, energy demand models, energy sypply models and environmental models (Figure 3.3). Energy demand, which usually is the driving force of the system, can also be provided as an exogenously input. Apart from balancing energy demand with primary energy supply, energy supply models may provide required capacities of energy system facilities and calculate system costs. Environmental effects are most usually related to the utilization of primary energy resources and energy conversion facilities.

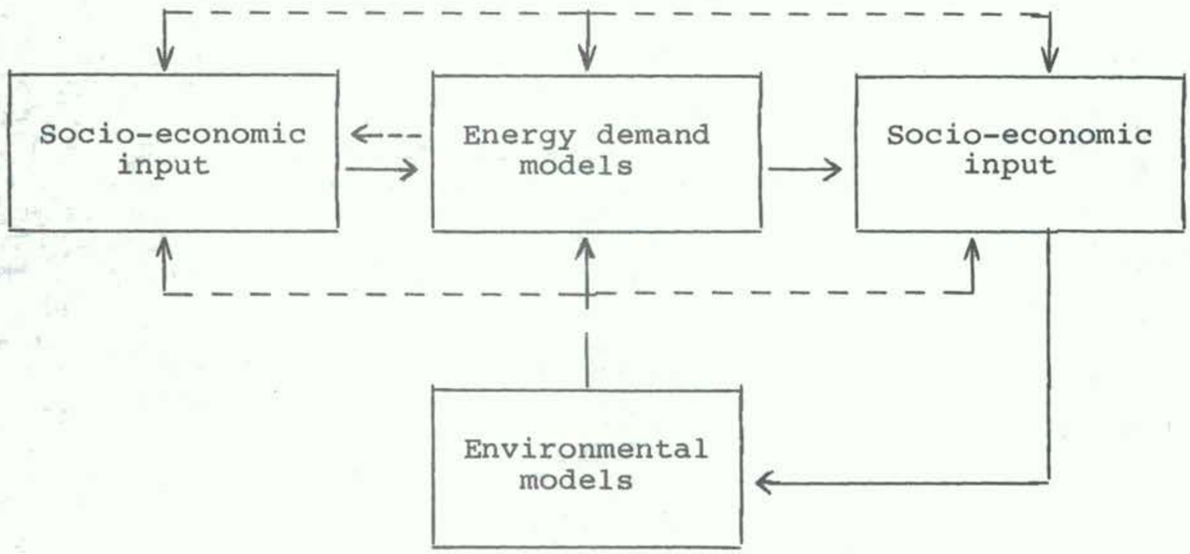

Figure 3.3 Main components and flow information in a set of energy-environmental models.

Two important characteristics of an energy-environmental model system are the depth of the environmental analysis and the implementation of the system feedbacks. There is a quite fundamental difference whether the environmental consideration is extended (1) to emissions only, (2) to the level of ambient environmental quality, (3) to arisings of health effects and other damages or (4) finally to the total value of the damages.

Emissions can often be estimated by relating them directly to utilization of power plants. Knowledge of total emissions is, however, seldom sufficient for proper inclusion of environmental aspects. More in-depth consideration of environmental effects requires sophisticated models, which are also more difficult to link to the energy supply models.

The feedbacks between the models - indicated by the dashed lines in Figure 3.3 - are often implemented by intervention of the model user rather than by formal mathematical links. This can be regarded a strength as well as a weakness in a systems analytic approach. The strength is that a broad spectrum of incommensurate impacts can be taken into consideration by the model user and/or the decision-maker. The initial assumptions may be corrected on the basis of informal assessments and preferences of the decision-maker without a formal validation of all impacts. One weakness of the informality is that the feedback procedure may in practice be omitted. Furthermore some of the basic advantages of a formal approach are partially lost, in particular the rigor and reproducability.

Apart from the large-scale, widely acclaimed energy system study (Häfele, 1981) the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, conducted in the late 1970's a research program designed to integrate regional energy and environmental management from a systems perspective. The programme represented an extension of work initiated at the University of Wisconsin-Madison, U.S. In four regional case studies the energy-environmental interaction were evaluated for the state of Wisconsin, U.S., for a region in the German Democratic Republic, for the Rhone-Alpes region in France as well as for Austria (Foell, 1979a,b). The programme resulted also in establishing the Wisconsin-IIASA set of energy/environmental models (WISE) for regional planning and management (Foell et al., 1981). The family of models together with some features of the case studies are presented in Appendix A.

E. COST-BENEFIT ANALYSIS

According to one definition cost-benefit analysis (CBA) is a systematic way of comparing positive and negative aspects of proposed courses of action in terms of a common monetary unit. Thus, in principle CBA would be an essential tool, supporting decisions on projects which aim at public welfare and involve costs (UNEP 1985b).

The CBA can be applied (1) to find out the justification of a single project, (2) to choose among the candidates the project which shows the largest benefits over costs, or (3) to determine the optimal level of an activity.

The decision rule for the first type states that a project is justified if the sum of social benefits exceeds the sum of the costs, including the social costs of any incidental environmental damages. For the second type, the project for which the surplus of benefits over costs is the highest, should be chosen. For the third type, the decision rule requires that the activity be expanded as long as its marginal benefits exceed its marginal costs (UNEP 1985b).

Compared with environmental impact assessment (EIA) and comparative assessment (CA), cost-benefit analysis (CBA) means a definitive step towards more comprehensive methods and direct steering of planning. In this respect, CBA is, in this categorization, preceeds only formal optimization:

EIA	C A	CBA OPTIMIZATION
←———	———	———→
acceptability assessment descriptive evaluation		steering of planning quantitative ranking

In principle, CBA could point the best course of action among the available alternatives taking into consideration all quantifiable implications. However, the quantification gives also reason to some doubts. Ignorance of unquantifiable impacts as well as valuation of non-market goods and "invaluables", as e.g. human life and scenic values, are issues often brought up by the skeptics.

UNEP has conducted an extensive study programme on applying of CBA in environmental decision-making. The work of the intergovernmental expert group organized by UNEP is summarized in four volumes of the UNEP Studies Series (Ahmad 1981a,-b; 1982; 1983). The programme was finalized by producing a two-volume book including a pragmatic introduction to the application of CBA as well as a choice of practical examples selected from among the over 150 case studies received by UNEP from different parts of the world (Ahmad et al., 1984). Furthermore, a separate study on the use of CBA in emission control of energy systems has been prepared for UNEP by the Technical Research Centre of Finland (UNEP, 1985). Therefore, the general issues of CBA will not be discussed in this report.

The CBA study of UNEP (1985b) includes two case studies as well as reviews of two comprehensive applications of CBA. The case studies carried out were:

- a cost-effectiveness analysis of complying with a SO_2 emission standard in a coal-fired power plant and
- a CBA analysis of reducing the radiation effects due to energy production.

The studies reviewed are the OECD cost-benefit study on SO_2 control (OECD, 1981) and an economic evaluation of alternative control technologies for a coal-fired power plant carried out by the French nuclear research centre at Fontany- aux-Roses (Mounier, 1981).

In Federal Republic of Germany cost-effectiveness analysis has been utilized to find out the most effective air pollution control measures in the state of Baden-Württemberg, (Friedrich et al., 1984). The observed damages to forest in Central and South Germany have increased very rapidly in recent years. Therefore, initiated by the government of the state, a working group consisting of government officials, directors of the regional electric power companies and scientists was set up to recommend strategies to reduce SO_2-emissions from public power plants, which contribute about 40 % of the total SO_2-emissions in Baden-Württemberg.

The first step of the study was to define a reference scenario that described the possible development of SO_2-emission from public power plants. The control measures required by law (for instance the installation of flue-gas desulphurization not later than July 1988) were taken into consideration in the reference case. Measures to quickly reduce the emissions in the years from 1984 to 1988 were then collected and described. For every measure considered, the cost-effectiveness ratio, that is the amount of money necessary to reduce the emissions by one kg SO_2, were evaluated. The measures having a cost-effectiveness ratio, that is lower or equal to that of an ordinary flue gas desulphurization plant required by law in the future (about 3-6 DM/kg SO_2), were recommended. These were:

A) Increased use of low sulphurous hard coal, especially in power plants that have so far not been retrofitted with fuel-gas-desulphurization.
B) Preferred use of power plants that have flue gas desulphurization (FGD) plants, (or at least realized first steps of them,) to the plants without FGD.
C) Extended use of natural gas in mixed fueled plants.
D) Earlier putting into operation of flue gas desulphurization plants than demanded by law.
E) Use of further possibilities to import electricity and re-export of the same amount of electricity later from power plants with flue-gas-desulphurization.

The recommended measures would reduce the SO_2-emissions from public power plants in Baden-Württemberg by approximately 25 % in the period 1984 to 1988. The power companies have agreed to execute these measures. The quick execution of the counter-measures is greatly owing to the direct involvement of the power companies in performing of the analysis.

According to the authors of the Baden-Württemberg study, the practical experiences gained during the study show that cost-effectiveness-analysis can deliver useful information for the assessment of various pollution control measures. Furthermore, the cost-effectiveness-analysis proved to be a helpful instrument to de-emotionalize the difficult discussions between the power industry who has to fullfill environmental regulations and politicians who are responsible for environmental affairs. Thereby, the method contributes t rational decision making.

Extending a cost-effectiveness-analysis as described above to a full cost-benefit-analysis would require a complete quantification in monetary terms of all the damages caused by the SO_2-emissions considered. This could however, not be done for several reasons discussed in preceding chapters. Therefor thee success of the Baden-Württemberg study to affect decision making in based on the general agreement that SO_2-emissions should be reduced. The study does not answer the crucial question, whether the reduction decided upon, was even close to the optimal magnitude.

F. ENVIRONMENTAL EFFECTS AND OPTIMIZATION OF ENERGY SYSTEMS

The prerequisite for utilizing mathematical optimization methods to select the best course of action in energy and environmental management problems is that these problems can be reduced into mathematical relationships. In many of these problems the multiplicity of criteria for judging the alternatives is pervasive. That is, more than one objective or goal is aimed to in selecting the course of action while satisfying the constraints dictated by environment, processes, and resources. Another characteristic of these problems is that the objectives are usually non-commensurable. Mathematically, these optimization problems can be represented as:

$$\begin{aligned} &\text{Min } [f_1(\bar{x}), f_2(\bar{x}), \ldots, f_k(\bar{x})]! \\ &\text{subject to: } g_i(\bar{x}) \leq 0 \quad i = 1, \ldots, m \end{aligned} \qquad (6.1)$$

where $\bar{x}$ is a n dimensional decision variable vector. $[f_1(\bar{x}), f_2(\bar{x}), \ldots, f_k(\bar{x})]$ is the set of objective functions to be minimized. (A maximization goal can be converted to a minimization goal by changing the sign of the objective function.) The problem consists of n decision variables, m constraints and k objectives.

In the special case all the objective functions and all the constraints are linear functions the problem can be represented in a matrix format. Usually, one of the constraints of a real problem is that the decision variables must have non-negative values. Hence, the problem can represented in the form:

$$\begin{aligned} &\text{Min } [\bar{c}_1\bar{x}, \bar{c}_2\bar{x}, \ldots, \bar{c}_k\bar{x}]! \\ &\bar{A}\,\bar{x} \leq \bar{b} \\ &\bar{x} \geq \bar{0} \end{aligned} \qquad (6.2)$$

where $\bar{c}_i$ is an n dimensional row vector consisting of the coefficients of the objective function $f_i(\bar{x})$. $\bar{A}$ is a m x n dimensional matrix containing the coefficients of the constraints functions and $\bar{b}$ is a m dimensional vector consisting of the constants of these functions. If there is only one objective function the problem can readily be solved using the linear programming (LP) techniques. In case of several non-commensurable objective functions the problem is more complex.

1. Energy system optimization models employing linear programming (LP) technique

Minimizing of total cost is usually the overriding objective in energy system optimization. There are three levels at which environmental factor can be accounted for in single-objective LP models. At the lowest level, the functions describing the magnitudes of environmental factor may only be monitored. In this case, they merely quantify the environmental factor of the cost minimizing energy supply strategy in natural units. On the next level, the magnitudes of environmental factor can be used as constraints in the LP model. Finally, they may included in the objective function thus directly participating in the optimization. The last of these three steps is straight-forward only if the values of environmental factor are known in monetary units. Otherwise, weighting of the different objectives includes value judgements by the analyst and is, indeed, finally equivalent to fixing the monetary equivalents of all the quantified environmental factors.

There is a large family of energy system optimization models employing linear programming technique. MESSAGE (Schrattenholzer, 1981) and the more sophisticated MESSAGE II have been developed at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. MARKAL (Abilock and Fishbone, 1979) is a model constructed to be used in multinational studies conducted by the International Energy Agency of OECD. The computer program was developed by research groups at the Brookhaven National Laboratory (BNL), U.S., and the Kernforschungsanlage Jülich, Federal Republic of Germany. The model hence has some of its roots in BESOM (Cherniavsky, 1974) and DESOM (Cherniavsky et al., 1979) developed at BNL.

With the exception of BESOM all the models mentioned above are suitable for optimizing the energy system over a given time horizon in a single optimization run, they thus can be called multi-period or dynamic LP models. In the dynamic mode, the models assume perfect foresight, i.e. decisions are implicitly assumed as taken with complete information about future prices, technologies available in the future etc. This seems, of course, to be quite unrealistic assumption.

The problem can be partially solved by analysing several alternative scenarios corresponding to different plausible futures. One may then proceed to recommend a robust choice of action leading to acceptable results in most or all of the scenarios.

LP models are usually demand-driven, i.e. feasible solutions are obtained only if all demands for energy are satisfied for every time period. However, there are some possibilities to incorporate energy conservation techniques into the models. Environmental effects are in these models usually taken into consideration at the level of emissions, which are related to the use of energy resources and energy conversation facilities.

In MARKAL there are several alternative objective functions programmed in the model. Among the objective criteria, one of which must be chosen for each run are: minimizing of total system cost, minimizing of usage of non-renewable energy resources and minimizing of the environmental-indicator objective function. A method for trade-off between the different criteria has been incorporated in the model. The trade-off between two objectives, e.g. minimizing of cost and environmental impacts, can be started with two optimization runs, in which each of the two objective functions are separately minimized while the value of the other is monitored only. The total cost and environmental impacts of the cost minimizing strategy, C, and of the environmental impacts minimizing strategy, E, are presented on a cost-environmental impact plot in Figure 3.4. The next step is minimizing the objective function of the environmental impacts subject to the cost objective function constrained to remain close to its value in strategy C. The resulting strategy is called CE. The purpose of searching CE is to find out, whether there is a way to reduce environmental impacts with no-or with a very moderate cost increase. If such a strategy is found, it is, in general, superior to the pure cost minimizing strategy C. In a similar way the minimization of cost subject to the minimum environmental impacts obtained from the strategy E leads to the strategy EC, which may be superior to the strategy E. Intermediate trade-off values can be obtained by minimizing the environmental function subject to the constraint:

$$c \leq c_C + k(c_E - c_C) \qquad (6.4)$$

where c_C and c_E are the cost of the strategies C and E, respectively. The parameter is varied having values $0 < k < 1$. The resulting trade-off curve is illustrated in Figure 3.4.

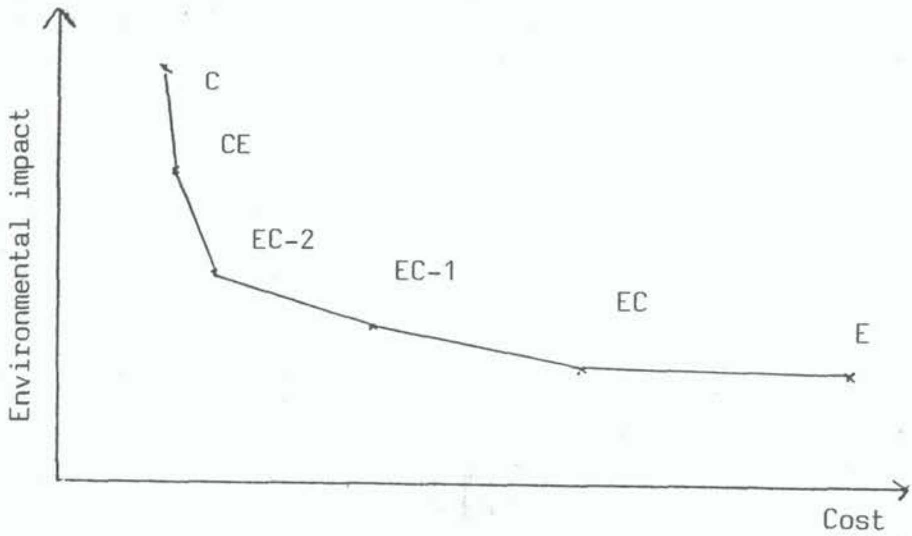

Figure 3.4 A Cost-Environmental Impact trade-off curve obtainable by six sequential optimizations with the MARKAL model.

A practical example of applying a LP model for regional energy-environmental analysis has been reported by Yingyun (1984). The model is used to evaluate the role of alternative energy sources in North China's urban region. The objectives evaluated in the case study are minimizing of total energy system cost and the impacts of SO_2 air contamination. The relative contributions to air pollution effects from unit pollution releases from various sources is accounted for by introducing a pollution effect coefficient for each emission source. The problem is then solved by minimizing one objective function while keeping the other under a given limit. Changing the constraint value and repeating the process several times, trade-off relationships similar to the one illustrated in Figure 3.4 are obtained.

2. Multiobjective optimization

Several methods have been developed for multiobjective optimization (see e.g., Hwang and Masud, 1979). For the decision-maker multiobjective optimization provides a systematic method to organize his preferences. The processes leading the decision-maker to articulate the necessary trade-off information are diverse. However, some trade-off, implicit or explicit, between the stated objectives is always required. In many multiobjective models the decision-maker is therefore required to intervene directly in the optimization process.

At the final step in all linear multiobjective optimization methods the user of the model, or the decision-maker cooperating with the user, must give relative weights to all objectives. This is equivalent to transforming various objectives into monetary terms, a step that is often not considered acceptable at the outset. During the process of searching for the proper relative weights, the user has gone through many alternative solutions, each optimal in its own way, and thus gained further insight in the alternatives. This may have helped in making the right choice for the relative weights - or the willingness to make the choice may be due to confusion and exhaustion caused by a complicated and misleading procedure.

Many different methods have been developed for aiding the process of choosing relative weights for the objective function. One particular method worth mentioning is fuzzy linear programming. This method is among the most straigth-forward ones and allows also taking into account imprecise constraints in addition of the normal precise ones. Similarly to all other methods for multiobjective optimization it must be stressed that the user must be fully aware of the significance and interpretation of the finally chosen parameter values, of lesser significance is the way these values were obtained.

G. INTEGRATED ANALYSIS OF ECONOMY-ENERGY-ENVIRONMENTAL SYSTEMS

Economic development, supply of energy and the quality of environment are closely linked to each others. The gradual degradation of the environment due to man-made pollution is going to bring about growing economic and social drawbacks. Nor can environmental protection policies be established without giving rise to some economic consequences. In developed countries, the cost of environmental policies has been estimated to range between 1 and 2 per cent of GNP. In the developing countries, the expenditure has so far been much lower. It has been estimated, that in order to control pollution efficiently in the Third World, it would be necessary to allocate about 0.5...1 per cent of the GNP for that purpose. Those figures should be seen in the light of the cost of pollution damage in developed countries, which amounts to 3 to 5 per cent of GNP. It is therefore quite understandable that on the policy planning level an integrated analysis of the economy-energy- environment complex is often craved for.

In the Netherlands, Nijkamp and his collegues have developed models and systems for integrated policy analysis. Apart from the economy-energy-environmental interactions, the national-regional interdependencies are considered in their studies. The ambitious systems, the development of which is still underway, include economic input-output models as well as models reflecting the income, employment, demographic effects, the balance of trade and the relationship between the private and public sector, etc. This is also why only general outlines of the systems could be illuminated in the book (Lakshamanan and Nijkamp, 1983), which yet was half devoted to these models. The main drawback of large integrated systems is specifically the complexity which makes them to appear almost impenetrable for an outsider.

The Strategic Environmental Analysis System (SEAS) has been developed by the U.S. Environmental Protection Agency (EPA) for assessing the impact of EPA policies on the economy and the environment. SEAS is an integrated series of computer implemented models and data bases. It provides medium-term forecasts (15 to 20 years) of economic activity and attendant resource usage and environmental pollution based upon input assumptions such as economy, population, energy demand and enviromental control measures (House 1977; Ratick and Lakshamanan, 1983).

The main functional areas of SEAS are economy, energy and environment. Each of these partitions is made up of many modules designed for a specific purpose that are interrelated within and between partitions by functional relationships and data matrices. Central to the economic partition of SEAS is INFORUM, a 200 sector dynamic input/output forecasting model. INFORUM provides year by year forecasts of activity level of each of the 200 economic sectors in response to macroeconomic projections of final demand. For many energy and environmental analysis, the 200 sector detail is not sufficient. Therefore, many economic sectors have been disaggregated into subsectors based upon the varied physical products within an economic sector or upon changing technological processes used to produce a particular product.

The modules of SEAS related to energy calculate the demand for energy, the supply patterns needed to meet that demand, and the capital needed to finance new supply activities. The demand for energy can either be exogenously input or derived within demand modules using the economic activity levels from INFORUM. This yearly forecast of energy demand is input to the Energy System Network Simulator (ESNS), a network flow model, that calculates the related energy resource consumption and energy supply technology activity level. The calculated activity levels for energy supply technologies are then input to the Energy Investment Module which estimates the investment pattern needed to support these levels. The investment requirement is used as feedback to INFORUM and to the energy demand modules.

The modules in the environment partition relate the level of activity calculated by the modules of the economic and energy partition to concomitant levels of residual (pollution) generation. There has been some development aimed at linking these generated levels of pollution to measures of ambient environmental quality and to environmental costs and benefits. These modules are, however, not well developed within the SEAS framework (Ratick and Lakshamanan, 1983). The levels of pollution abatement activity are supplied exogenously according to the policy decisions. The investment and operation and maintenance costs of pollution control techniques are then calculated and fed back to the modules in the economic partition. The REGION module allocates the pollution generation to regions. The interactions between the main modules of SEAS, seen from the point of view of the energy partition, are illustrated in Figure 3.5.

According to Ratick and Lakshamanan (1983) SEAS is large, flexible, transparent and in many ways complex predictive tool that can be applied in many different situations and for a wide variety of different purposes. Due to its scope the system provides a comprehensive view of the interactions among economic, energy and environmental activities. The integrated nature of the system assures a high degree of consistency in the data used, assumptions made and algorithms utilized to make its projections. Its large and complex structure permits a sufficient level of detail to be achieved in many policy applications.

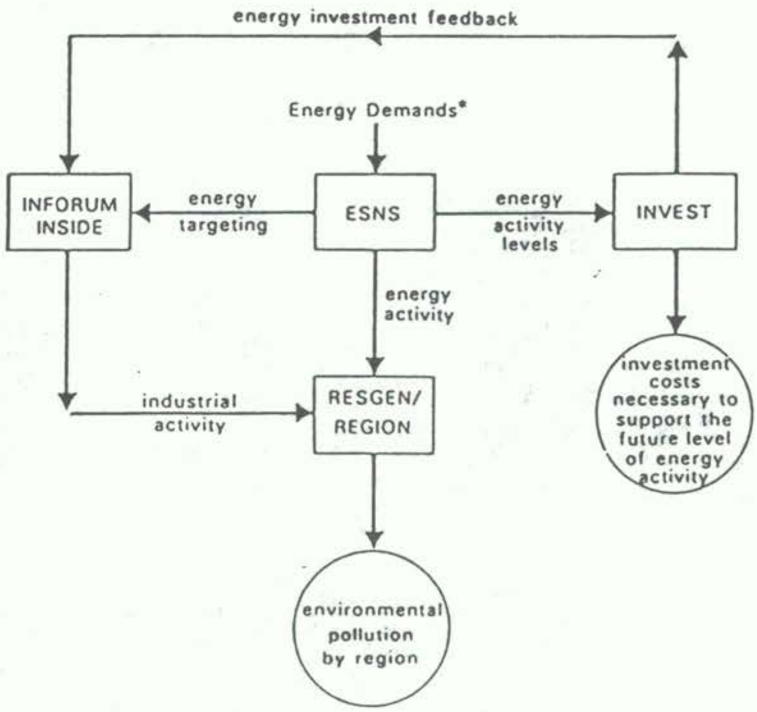

Figure 3.5 The interactions between the main modules of SEAS (Ratick and Lakshamanan, 1983).

The paradox of large integrated systems is that the attributes which enhance their usefullness also plague their acceptance. The scope and complexity of these systems makes the understanding of the entire system difficult for the user. Continued use and successful application of the system can provide informal "in vivo" system verification. However, the user often, quite understandably, require that such a system should first be verified before it is used.

The model system of extent of SEAS is obviously useful for obtaining general information about the activities affecting environment in a large country like U.S.A. or a group of countries like Western Europe. In this way it may help in directing the overall environmental policy on a national or even multinational level. The basic ideas of such a model system must be straightforward for obtaining sufficient transparency. The complexity due to the large number of details is more readily acceptable than that due to complicated internal relationships in the model. The transparency of a large model system of straightforward structure suffers most from the need for aggregation, which is always somewhat arbitary. In a sense the transparency suffers from the attempt to simplify the model by reducing the number of details to a manageable level.

CAHPTER IV

EXAMPLES OF AVAILABLE ENERGY-ENVIRONMENT MODELS

A THE WISCONSIN-IIASA SET OF ENERGY/ENVIRONMENT MODELS (WISE)

1. Institutional framework

The International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, conducted in the late 1970's a research program designed to integrate regional energy and environmental management from a systems perspective. The program represented an extension of work initiated at the University of Wisconsin-Madison, U.S. The regional energy/environment management research complemented IIASA's Energy Systems Program, which focused primarily on global aspects of energy (Häfele, 1981).

Four regional case studies were carried out within the research framework. The first study originated at the University of Wisconsin-Madison, in the form of a policy-oriented study of energy systems in the state of Wisconsin. This work was then extended within a comparative framework for applications to three different areas, the German Democratic Republic, the Rhone-Alpes region of France, and Wisconsin. The methodology and the three case studies have been described in a book published in 1979 (Foell, 1979). Subsequently, the research group undertook a two-year study of the energy/environment system in Austria (Foell et al., 1981).

2. Systems analytic approach

Scenario building was employed as a device for analyzing alternative energy and environment policies and strategies in the regions. The policy issues studied were human settlements, transportation systems, energy supply and environmental protection and resource conservation. The framework for a policy set scenario was described using the following terms:

- population,
- economic growth and structure,
- human (urban) settlement location and form,
- technologies of energy use,
- transport systems for people and goods,
- primary energy conversion and supply technology (including electricity generation),
- environmental protection.

Table A.1 gives an overview of these characteristics for the four scenarios analyzed in the Austrian case study (Foell et al., 1979). The general framework was then used to provide the exogenous functions, boundary conditions, and constraints for the models used to evaluate the alternative futures conducted from the scenario assumptions.

The systems analytic process that links issues, scenarios and models was summarized by three main steps Foell et al., 1981):

a) Identification and choice of issues;
b) Definition of the scenario framework and the assumptions;
c) Use of the models to build and evaluate the alternative futures.

Figure 4.1 shows this process schematically. The models produce "system indicators", e.g. energy requirements and environmental impacts, which are useful in evaluating alternative strategies.

Table 4.1. Overview of the scenarios analyzed in the Austrian case study (Foell et al., 1979)

Summary characteristics		Scenario S1 (Base Case)	Scenario S2 (High Case)	Scenario S3 (Low Case)	Scenario S4 (Conservation Case)
Socio-economic structure	Population	Average Austrian growth rate of 0.22%/yr			
	Human settlements	Migration important: rural to urban; Vienna declining; western cities grow more rapidly			
	Economy	Medium growth rate 1970–1985: 3.30%/yr 1985–2015: 1.76%/yr	High growth rate 1970–1985: 3.43%/yr 1985–2015: 2.73%/yr	Low growth rate 1970–1985: 3.23%/yr 1985–2015: 1.21%/yr	Low growth rate 1970–1985: 3.23%/yr 1985–2015: 1.21%/yr
Lifestyle	Personal consumption	Current trends in personal consumption	Higher consumption than in S1	Lower consumption than in S1	Lower consumption than in S1
	Transportation	Car ownership 300 vehicles/1,000 population	Car ownership 400 vehicles/1,000 population	Car ownership 250 vehicles/1,000 population	Car ownership 300 vehicles/1,000 population
	Housing	Bigger new homes (0.8 m^2/yr) Emphasis on electrical appliances and convenient fuels	New home size increases faster than in S1 High emphasis on electrical appliances and convenient fuels	New home size increases more slowly than in S1 Less emphasis on electrical appliances and convenient fuels	Same as S3
Technology	Industry	Overall decrease in energy intensiveness through significant penetration of energy conserving technology	General increase in intensiveness	Overall decrease in energy intensiveness through significant penetration of energy conserving technology	Significant decrease in energy intensiveness through vigorous development and implementation of energy conserving technology
	Transportation	Car efficiency 8.9 liter/100 km	Car efficiency 12.3 liter/100 km	Car efficiency 8.9 liter/100 km	Car efficiency 7.0 liter/100 km
	Housing	1971 insulation standard	1971 insulation standard	By 2000 new homes 40% better than 1971 insulation standard	By 2000 new homes 55% better than 1971 insulation standard
	Energy supply	Decreased emphasis on coal			
		Electricity demand grows more rapidly than total end-use energy demand			
		Medium nuclear growth Adequate oil and gas supply	High nuclear growth Adequate oil and gas supply	Low nuclear growth Adequate oil and gas supply	No nuclear growth Constrained oil supply
Environment	Environmental regulations	Proposed SO_2 oil desulfurization regulations by 1981 plus U.S. emission limits of SO_2, all sources, by 2000			
		0.50 of U.S. emission limits on SO_2, point sources, by 2015	0.42 of U.S. emission limits on SO_2, point sources, by 2015	0.71 of U.S. emission limits on SO_2, point sources, by 2015	Same as S3
		1.18 of U.S. emission limits on particulates, industry point sources, by 2015	1.0 of U.S. emission limits on particulates, industry point sources, by 2015	1.60 of U.S. emission limits on particulates, industry point sources, by 2015	Same as S3
		U.S. emission limits of particulates, electric power plants, by 2015			

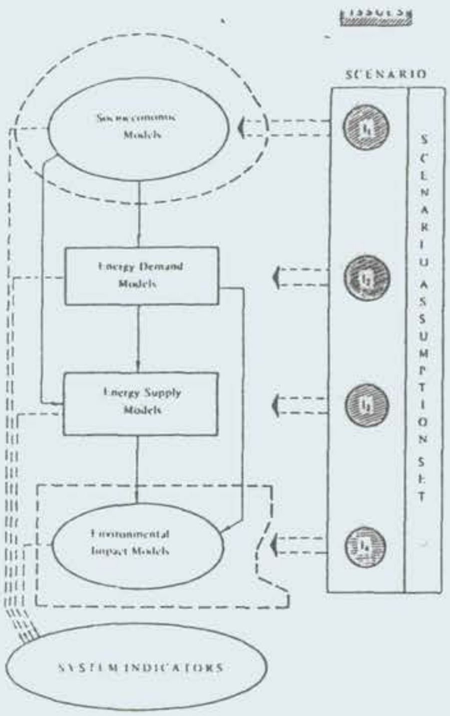

Figure 4.1. Relationship between issues, scenarios and models (Foell, 1979).

3. Structure of the family of models

The models of the WISE set describe four major energy/environment system components:

- socioeconomic activities,
- energy demand,
- energy supply,
- environment.

The flow of information between these components is depicted in Figure 4.2. The flow was summarized as follows (the numbers in parentheses correspond to the flows shown in Figure 4.2):

a) Regional socioeconomic information (e.g. population, settlement patterns, economic activity) is provided exogenously (1) and/or by models (2).

b) The socioeconomic information serves as input (3) to energy demand models (4), which are structured according to economic sector (e.g., industry, service, or agriculture) or by technological process (e.g., heating, cooling, or lighting). In general the outputs of the energy demand models are in the form of annual demand, usually specified by fuel.

c) The outputs of the energy demand models form the inputs (5) to energy supply models, which in turn are used to calculate primary energy requirements, conversion and transport facilities needed, supply system costs, etc. In most of the case studies conducted by the research group, supply was directly matched to demand within a framework of constraints. A formal optimization model was applied only in the Austrian case study.

d) The energy flows in the supply system (6) and the end-use energy serve as inputs (7,8) to the environmental impact models (9). These models calculate impacts on a broad spectrum of areas including human health and safety, on a systemwide and localized basis.

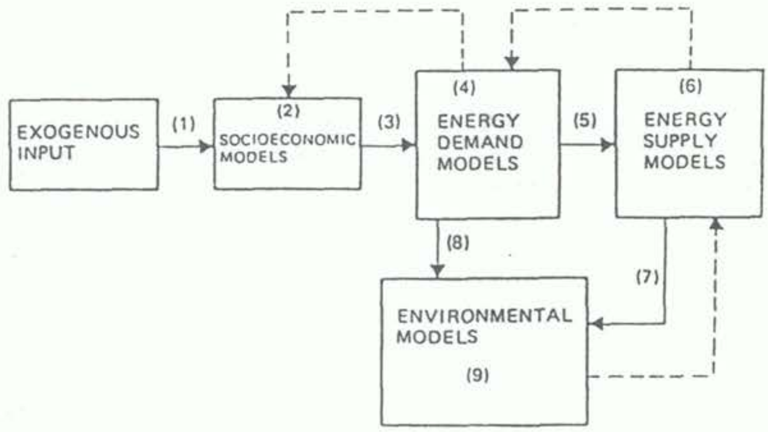

Fig 4.2. Flow of information among Wisconsin-IIASA energy/environmental models (Foell et.al., 1981).

The feedbacks between the models indicated by the dashed lines in Figure 4.2 are implemented by intervention of the model user and not by formal mathematical links. However, no actual feedback iterations or changes of the initial scenario assumptions based on the results of model runs are reported in the case study documentations. Therefore, the environmental parts of the analyses were virtually reduced to environmental impact assessments, in which a large number of quantified environmental effects were tabulated.

4. Socioeconomic and energy demand models

The socioeconomic models employed by the research group included a population model and a macroeconomic input-output model. In the regional case studies major emphasis was placed on the demand of energy. The energy demand modeling and assessment were carried out at the point of end-use demand. The energy-demand was classified into five sectors, covering the residential, commercial/service, industrial, agricultural, and transportation sectors. A separate demand model was developed to examine the energy consumption within each sector. The transport sector demand models were employed also to calculate traffic-related air pollution emissions.

5. Energy Supply Models

In most case studies no formal, computer-implemented energy supply model was used. Instead of applying a model, a simple demand/supply balance technique was employed, in which energy supply was matched to energy demand taking into consideration the region's historical experience and future plans for electricity and district heat generation. Only in the Austrian case study a formal resource allocation model was used to a limited extent. The model used was the Brookhaven Energy System Optimization Model (BESOM). BESOM is a static energy system optimization model applying the linear programming technique. In the Austrian case study BESOM was employed to generate the cost minimizing energy supply mix for a chosen reference year in three of the four scenarios evaluated in the study.

6. Environmental models

Five models are included in the Wisconin-IIASA set of environmental models. The Reference Energy System Impact Model calculates impacts associated with different fuel chains. These impacts are not treated on a site-specific basis in the model. The Air Pollution Dispersion Model, a local system model, calculates the urban exposure to various air pollutants. It requires a Localization Model to interface with the energy demand models, which do not produce output at a sufficient level of spatial disaggregation. The SO_2 Health Impact Model is used in combination with both the Reference Energy System Model and the Air Pollution Dispersion Model to calculate SO_2-related human health impacts. The River Body Thermal Pollution Model was used to a limited extent to study the thermal effects of power plants on rivers. The Reference Energy System Impact Model, the Air Pollution dispersion Model and the SO_2 Health Impact Model are described below.

a) The Reference Energy System Impact Model

The Reference Energy System Impact Model is designed to calculate quantified environmental impacts associated with the supply of primary energy, conversion of primary energy into secondary energy sources, and processing and reprocessing of fuels to meet the energy requirements of a given region. The impacts are calculated on an aggregate level for a region as a whole. The total annual quantified impacts associated with a particular reference energy system are calculated by multiplying the use of each energy source by a impact factor and adding the resulting impacts up. There are separate impact factors for each energy source and each type of environmental impact. The impact factors may also change from one year to the next.

A difficulty in applying the reference Energy System Impact Model is, of course, associated with fixing the impact factors. The factors can be deduced from literature and historical statistics. However, their future values are difficult to predict. Also the deduced factors are subject to great uncertainties.

Table 4.2 provides an example listing of the results of a model run for the Austrian case study. The listed impacts are associated with the production of 3.2 TWh ($3.2\ 10^9$ kWh) of electricity at coal-fired utility plants under current system conditions.

b) The Air Pollution Dispersion Model

The Air Pollution Dispersion Model (Dennis, 1978) is designed to describe air pollution dispersion on an urban scale with minimum data requirements and without the direct use of complex and large dispersion models. The model calculates the annual average ground-level concentration of SO_2 in an urban area due to the emissions in this area (the "self- imposed" concentration). The total urban concentration can be obtained by adding the rural background concentration,

which usually is much lower than the self-imposed urban concentration. The underlying assumption is that the mobility of the population within an urban area is high relative to the spatial variation of ground-level pollution concentrations. Hence, an annual average ground-level concentration averaged spatially over the entire urban area is sufficiently precise indicator for health impact analysis.

For an urban area most sources of emissions automatically fall into three classes. They are:

1. Low-level area sources, as for example, transportation and residential emissions;
2. Medium-level point sources, as for example, industrial and district heating stacks; and
3. High level point sources, as for example, large electricity generating plants.

The dispersion characteristics of the three classes are distinctly different. As a rule of thumb, a ton of pollutant emitted in an urban area by low-level area sources has ten times the effect on the urban area impacts as a ton emitted from medium-level point sources and a 100 times the effect as a ton emitted from high-level point sources (Dennis, 1978).

The self-imposed urban air pollution concentration in the city j, is calculated for the urban emissions UE_{ij} in each of the three classes and then summed, i.e.,

$$UC_j = \sum_i D_i(R_j) \cdot UE_{ij} \qquad (4.2)$$

where i is the emission class and R_j is the average radius of city j. $D_j(R)$ is the dispersion parameter.

Table 4.2 Sample listing for the Austrian case study, (Foell et al. 1981)

Impact	Unit	Quantity
Fuel resource, Efficiency, and Soild waste		
1 Coal requirement after cleaning losses	Tons	.305 + 07
2 Transportation and handling loss of coal	Tons	.305 + 05
3 Coal plant thermal discharge to water	kWh (t)	.572 + 10
4 Coal plant thermal discharge to air	kWh (t)	.111 + 10
5 Total train-miles for coal shipments	Miles	.134 + 05
6 Input energy required throughout coal fuel system	kWh (t)	.101 + 11
7 Ash collected at coal power plant	Tons	.296 + 06
8 Sulfur retained at coal power plant	Tons	000
9 Limestone mined for sulfur removal	Tons	000
10 Coal cleaning plant solid waste	Tons	.101 + 07
Land use		
11 Land disturbed for surface mining of coal	Acres	.257 + 03
12 Land disturbed for coal surface mining - not reclaimed	Acres	.257 + 02
13 Land subsidence from underground coal mining	Acres	.439 + 03
14 Land for ash disposal at power plant	Acres	.640 + 01
15 Land for sulfur sludge disposal at power plant	Acres	000
16 Land for disposal of solid waste from underground mining	Acres	.194 + 01
17 Land for disposal of solid waste from cleaning	Acres	.864 + 01
18 Waste storage area for coal fuel cycle	Acres	.170 + 02
19 Land use at plant and fuel cycle facilities -- coal	Acres	.967 + 03
Impacts on water		
20 Acid mine drainage from coal mining (mostly water)	Tons	.212 + 06
21 Sulfuric acid in coal mine drainage	Tons	.148 + 04
22 Dissolved iron in coal mine drainage	Tons	.370 + 03
23 Siltation from surface mining	Tons	.184 + 04
24 Coal cleaning plant blackwater solids	Tons	.102 + 04
Impacts on air		
25 Flyash emission at coal power plant	Tons	.616 + 04
26 Sulfur dioxide emission at coal power plant	Tons	.305 + 05
27 Nitrogen oxides (NO_x) emission at coal power plant	Tons	.120 + 05
28 Carbon dioxide emission at coal power plant	Tons	.342 + 07
29 Carbon monoxide emission at coal power plant	Tons	.531 + 03
30 Hydrocarbon emission at coal power plant	Tons	.171 + 03
31 Aldehyde emission at coal power plant	Tons	.342 + 01
32 Mercury emission at coal power plant	Tons	.604 + 01
33 Beryllium emission at coal power plant	Tons	.247 + 00
34 Arsenic emission at coal power plant	Tons	.616 + 00
35 Cadmium emission at coal power plant	Tons	.616 − 02
36 Lead emission at coal power plant	Tons	.111 + 01
37 Nickel emission at coal power plant	Tons	.247 + 01
38 Vanadium emission at coal power plant	Tons	.203 + 01
39 Uranium (U-238) or Ra-226 emission at coal power plant	Curies	.555 − 01
40 Thorium (Th-232) or Ra-228 emission at coal power plant	Curies	.125 − 01
41 Coal cleaning plant dust emission	Tons	.102 − 01
Health impacts		
42 Coal mine accidents − fatalities	Deaths	.260 + 01
43 Coal mine accidents − nonfatal injuries	NFI	.816 + 03
44 Coal mine accidents − severity in person-days-lost	PDL	.571 + 06
45 Coal cleaning plant occupational fatalities	Deaths	.457 − 01
46 Coal cleaning plant occupational nonfatal injuries	NFI	.427 + 01
47 Coal cleaning plant occupational severity	PDL	.445 + 03
48 Coal transportation accidents − occupational fatalities	Deaths	.430 − 02
49 Coal transportation accidents − occupational nonfatal injuries	NFI	.430 + 00
50 Coal transportation accidents − occupational severity	PDL	.391 + 02
51 Coal transportation accidents − public fatalities	Deaths	.497 − 01
52 Coal transportation accidents − public nonfatal injuries	NFI	.128 + 00
53 Coal transportation accidents − public severity	PDL	.324 + 03
54 Coal power plant accidents − occupational fatalities	Deaths	.131 − 01
55 Coal power plant accidents − occupational nonfatal injuries	NFI	.576 + 00
56 Coal power plant accidents − occupational severity	PDL	.119 + 03
57 Cases of total disability from black-lung disease	Cases	.659 + 01
58 Cases of simple black-lung disease (some disability)	Cases	.144 + 02
59 Public fatalities from acute SO_2 exposure	Deaths	000
60 Days of aggravation of heart and lung disease from SO_2	Days	.102 + 04
61 Excess asthma attacks from acute SO_2 exposure	Attacks	.260 + 03
62 Total occupational fatalities, health and accident, for coal	Deaths	.925 + 01
63 Total occupational nonfatal injuries for coal	NFI	.836 + 03
64 Total occupational severity for coal	PDL	.972 + 05
65 Total deaths in coal fuel cycle − annual	Deaths	.930 + 01
66 Total nonfatal injuries in coal fuel cycle − annual	NFI	.212 + 04
67 Total person-days lost in coal fuel cycle -- annual	PDL	.988 + 05

The main assumptions and simplifications used in deducting of the dispersion parameters D_i:s are as follows:

- D_i:s are dependent of the average radius of city, which is related to the diluting air volume.
- D_i:s are sensitive to meteorological conditions, i.e. to the frequency of occurrence of different atmospheric stability conditions and wind speeds.
- D_i:s are formulated for a uniform wind-rose, i.e. the distribution of wind directions has not been accounted.
- No special allowance is made for anomalous terrain and geographic effects. However, many of these effects are embedded in the meteorological statistics.
- D_i:s are not sensitive to the locations of the emissions in the urban area.
- D_i:s are not sensitive to the surface roughness of the urban area.
- D_3 is sensitive to the average stack height, but otherwise D_i:s are insensitive to the mix of the stack parameters within the emission classes.

These features are thoroughly discussed and the associated uncertainties are assessed with model simulations by Dennis (1978). As one might expect, the uncertainties due to the simplifications are highest in the case of high level point sources. However, the impact of high-level sources to the ground-level SO_2 concentrations is relatively low in most urban areas. Based on the above assumptions the dispersion parameter $D_i(R)$ is presented as a composition of the set of dispersion parameters $D_{ikm}(R)$, which describe wind speed m and atmospheric stability k, i.e.

$$D_i(R) = \sum_{k,m} ff_{km} D_{ikm} \qquad (4.3)$$

where ff_{km} (=meteorological frequency factor) is the frequency of occurrance in time of the particular atmospheric stability k, and the wind speed, m. The atmospheric stability is defined by three subdivisions. They are:

k = 1 unstable atmosphere,
k = 2 neutral atmosphere,
k = 3 stable atmosphere.

The wind speed is defined by four general subdivisions. They are:

m = 1 high wind speed (> 7.5 m/s at 10 m height),
m = 2 moderate wind speed (5-7.5 m/s)
m = 3 low wind speed (2-5 m/s)
m = 4 very low wind speed and/or calm (below 2 m/s).

Hence, there are twelve (3x4) possible combination of atmospheric stability (k) and wind speed (m). However, some of these combinations, e.g. the high wind speed, stable atmosphere case, are very unlikely.

The form of dispersion parameter D_{ikm} is

$$\ln D_{ikm}(R) = a_{ikm} + b_{ikm}(\ln R) + c_{ikm}(\ln R)^2 \qquad (4.4)$$

where a_{ikm}, b_{ikm} and c_{ikm} are constants tabulated by Dennis (1978). For high-level point sources a stack adjustment factor for D is also provided. The coefficients are reproduced in Tables 4.3 to 4.6.

The Air Pollution Dispersion Model seems to be the best-documented and verified among the wise models. The method has been validated in detail for three cities, namely Madison and Milwaukee, Wisconsin (U.S.) and Vienna, Austria. For the Wisconsin cities detailed isopleths from a calibrated dispersion model were available for validation. For the three cities, calculated concentration was within 20 % of the expected exposure based on monitoring data and within 5 % of the expected exposure based on the isopleths provided by a complex air pollution dispersion model. The validation results are shown in Table 4.7 for Milwaukee, and in Table 4.8 for Vienna. The agreement for both cities is good. The relative impacts ($\mu g/m^3$ per ton of emission) of the low-level area sources, medium-level point sources and high-level point sources are in the case of Milwaukee in the ratio 46:5:1. In Vienna the same ratio is 7 9:3:1.

The Air Pollution Dispersion Model provides the annual average SO_2 concentration for an urban area. The damage models, e.g. the health impact model discussed below, may, however, require shorter temporal averages, e.g. the maximum 24 h concentration. The method applied by the IIASA research group was to approximate the concentration distribution with a log-normal distribution. Any shorter-term average can thus be derived from the annual average by using the standard geometric deviation (GSD) of the distribution. The GSD was obtained from empirical data relating GSD and city size; in general the GSD decreased with increasing city size. Unfortunately, the relationship of the GSD to the city size is not given presented in the study case reports.

Table 4.3. Coefficients for the low-level area source dispersion parameters, D_1 (Dennis 1978).

$$\ell n(D_{1km}) = a_{1km} + b_{1km}(\ell nR)$$

D: units of $10^{-4}\mu g/m^3/t$ per unit time

R: units of kilometers

Atmospheric Stability (k)	Wind Speed (m)	SCA Dispersion Kit Coefficients	
		a_{1km}	b_{1km}
Unstable	Very low	6.3909	-1.4922
	Low	6.0746	-1.7241
	Moderate	5.9253	-1.7124
	High	5.7998	-1.6815
Neutral	Very low	7.7780	-1.5919
	Low	6.8432	-1.5998
	Moderate	6.2450	-1.6191
	High	5.8925	-1.6236
Stable	Very low	7.3975	-0.8715
	Low	7.2562	-1.2407
	Moderate	6.9757	-1.4334

Table 4.4. Coefficients for the medium-level point source dispersion parameter, D_2 (Dennis 1978).

$$\ell n(D_{2km}) = a_{2km} + b_{2km}(\ell nR) + c_{2km}(\ell nR)^2$$

D: units of 10^{-4} $\mu g/m^3/t$ per unit time

R: units of kilometers

Atmospheric Stability (k)	Wind Speed (m)	SCA Dispersion Kit Coefficients		
		a_{2km}	b_{2km}	c_{2km}
Unstable	Very low	2.6037	-0.4189	-0.1112
	Low	3.2192	-0.8274	-0.0533
	Moderate	3.3518	-1.0820	-0.0074
	High	3.1275	-1.1379	0.0
Neutral	Very low	1.0435	0.4930	-0.2277
	Low	2.6678	-0.3045	-0.1340
	Moderate	2.9945	-0.6299	-0.0940
	High	2.8857	-0.8039	-0.0695
Stable	Very low	-0.7426	1.2169	-0.2785
	Low	0.8637	0.6345	-0.2300

Table 4.5. Coefficients for the high-level point source dispersion parameter, D_3 (Dennis 1978).

$$\ell n(D_{3km}) = a_{3km} + b_{3km}(\ell nR) + c_{3km}(\ell nR)^2$$

D: units of 10^{-4} $\mu g/m^3/t$ per unit time

R: units of kilometers

Atmospheric Stability (k)	Wind Speed (m)	SCA Dispersion Kit Coefficients		
		a_{3km}	b_{3km}	c_{3km}
Unstable	Very Low	1.1710	0.8849	-0.2837
	Low	1.0344	0.4271	-0.2301
	Moderate	0.5996	0.3266	-0.2164
	High	0.6470	0.2506	-0.2316
Neutral	Very Low	-30.8007	19.5370	-3.1169
	Low	-13.8196	7.9813	-1.2264
	Moderate	-9.3807	6.2428	-1.1238
	High	-6.2753	4.2501	-0.8205
Stable	Very Low	-18.3797	5.9778	0.0
	Low	-44.5100	20.8940	-2.6537

Table 4.6. Stack height adjustment factors for the high-level point source dispersion parameters D_3 at given stack heights. (Dennis 1978).

Stack Height (m)	Ratio to Reference Stack Height	High-level Point Source SCA Dispersion Parameter (D_3) Adjustment Factor
80	0.48	3.54
100	0.61	2.48
150	0.91	1.10
165	1.00	1.00
200	1.21	0.79
250	1.52	0.54
300	1.82	0.33

Table 4.7. Air Pollution Dispersion Model validation for Milwaukee, Wisconsin (U.S.). SO_2 comparison, 1973. (Dennis 1978).

	SO_2 Emissions (t)	SCA Method Exposure ($\mu g/m^3$)	Dispersion Model Exposure ($\mu g/m^3$)	Monitoring Data ($\mu g/m^3$)
Area Sources (D_1) Transportation	743	18.7	17.3	N.A.
Residential & Commercial	8,605			
Point Sources (D_2) Industry	7,486	1.6	7.7	
Power Plants (D_3)	139,800	6.1		
Subtotal	156,634	26.4	25.0	
Background		5.0	5.0	
TOTAL		31.4	30.0	35-40

N.A. Not Applicable

Table 4.8. The Air Pollution dispersion Model validation for Vienna, Austria. SO_2 comparison, 1974. (Dennis 1978).

	SO_2 Emissions (t)	SCA Method Exposure ($\mu g/m^3$)	Monitoring Data ($\mu g/m^3$)
Area Sources (D_1) Residential & Commercial	14,256	60.5	N.A.
Point Sources (D_2) Industry	11,462	2.1	
Power Plants (D_3)	14,877	0.8	
Subtotal	40,595	63.4	
Estimated Background		2-5	
TOTAL		65-68	69

N.A. Not Applicable

c) The SO_2 Health Impact Model

The SO_2 Health Impact Model provides a quantified estimate of human health impacts associated with a given SO_2 air pollution exposure. The model uses the annual arithmetical mean SO_2 exposure and the population exposed as inputs. The impacts are expressed in terms of excess morbidity and premature mortality in certain groups of at-risk population. The follow of calculations in the model is shown in Figure 4.3.

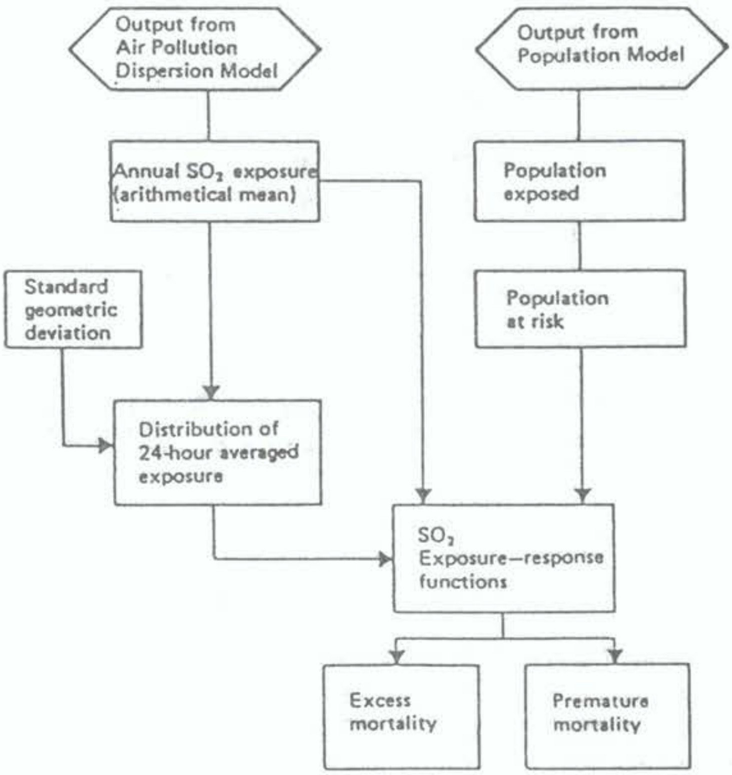

Figure 4.3. Flow of calculations in the SO_2 Health Impact Model (Foell et al., 1981).

The dose-response functions used in the health impact model link health effects rather to the acid-sulphate aerosol exposure than to the SO_2 exposure. The relationship of 24-hour levels of suspended sulphate to SO_2 concentration was presented in the form:

Suspended sulphates ($\mu g/m^3$) = 9 + 0.003 · SO_2($\mu g/m^3$). (4.5)
The dose-response function set is presented in Table 4.9.

Table 4.9 Dose-response functions linking acid-sulphate exposure to selected health effects (Foell et al., 1981).

Adverse health effect[a]	Threshold concentration of suspended sulfates for given exposure duration	Slope	Intercept
Increased daily mortality (acute episodes)	25 $\mu g/m^3$ for 24 hours or longer	0.00252	−0.0631
Aggravation of heart and lung disease in elderly patients	9 $\mu g/m^3$ for 24 hours or longer	0.0141	−0.127
Aggravation of asthma	6–10 $\mu g/m^3$ for 24 hours or longer	0.0335	−0.201
Excess acute lower respiratory disease in children	13 $\mu g/m^3$ for several years	0.0769	−1.000
Excess risk for chronic bronchitis			
Nonsmokers	10 $\mu g/m^3$ for up to 10 years	0.1340	−1.42
Cigarette smokers	15 $\mu g/m^3$ for up to 10 years	0.0738	−1.14

[a] The adverse effects refer to the percentage by which the mortality or morbidity rates exceed the expected rates, e.g., a 100 $\mu g/m^3$ sulfate concentration for one day is estimated to increase expected mortality on that day by 18.9 percent.
NOTES: The threshold concentrations for increased daily mortality, aggravation of asthma, and excess acute lower respiratory disease in children are based on four studies, the threshold concentration for aggravation of heart and lung disease in elderly patients is based on two studies, and the threshold concentrations for excess risk for chronic bronchitis are based on six studies.

7. Concluding remarks

"We believe that the value of the work described here lies not in the originality or sophistication of the individual methods and models, but rather in the process and framework that integrate them to describe the overall energy/environment system of a region" is the advisable statement made by the model-builders themselves (Foell et al. 1981). Some of the models constituting the WISE system are, indeed, rather simple and coarse. With the exception of the Air Pollution Dispersion Model, the individual models appear to have little value outside the system. On the other hand, one should bear in mind that the system framework applied enables refinement of individual models and implementation of more sophisticated models in the system.

B. ELECTRICITY PRODUCTION FOR A RAPIDLY GROWING CITY IN A DEVELOPING COUNTRY

1. INTRODUCTION

In this case study, we consider problems appearing in the planning of electricity production in a rapidly growing city, when local conditions emphasize the importance of environmental considerations. The study considered is not one that has actually been performed for real planning needs, nor does it refer to any real city. The properties of the city and of the planning situation are, instead, chosen to represent a combination of the properties of several actual cases. An attempt has been made to keep the study as realistic as possible without referring to any real planning case. For the case of presentation the details of the case are kept relatively simple. The same steps can and should, however, be taken in a real planning situation.

The general setting of the planning situation is as follows:

- The city is situated in the tropics on a coastal location and surrounded by mountains and hills on the other three sides at a distance of 20-40 km from the city centre.
- The city has a rapidly growing population of about 5 million. The total area of the city is about 500 km^2. The city centre, where the governmental and other major public buildings, hospitals etc. are located, covers 200 km^2. Map of the city is shown in Fig. 4.4
- The electricity used in the city area is presently produced by three oil fired power plants, each of capacity 320 MW net. For peak load and reserve needs there are several gas turbine plants with the combined capacity of 500 MW. The environmental effects due to the gas turbine plants are small, therefore they are not considered further in this case study. The locations of the power plants are shown on the map (Fig. 4.4).
- The rapid growth in the consumption of electricity leads in near future to the need of 1000 MW additional supply of electricity. Three basic alternatives are considered for satisfying this need:
  - (i) three new oil fired power plants of similar type as the existing ones to be situated in the city area,
  - (ii) one large four unit coal fired power plant of capacity 4 x 250 MW situated at the periphery of the city,
  - (iii) a coal fired plant as in case (ii), but situated about 100 km from the city.

  For each basic alternative, various levels of emission control are considered. The possible locations in the city area are shown on the map (Fig. 4.4).

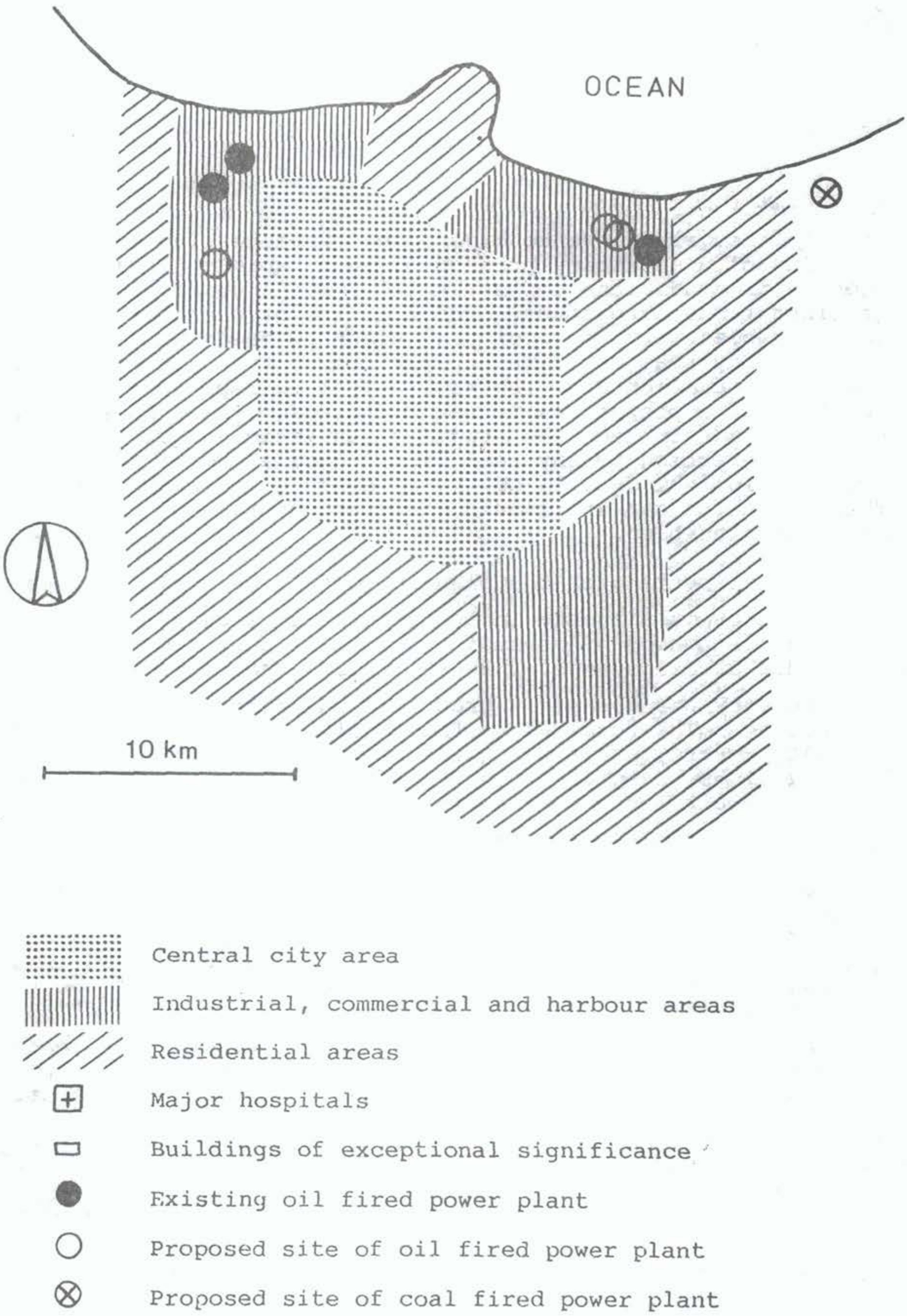

Fig. 4.4 Map of the city for the case study.

The goal of the study is to provide the decision makers with a comprehensive view of the economic and environmental consequences of the various alternatives. No attempt is made to give the total economic equivalence of the environmental effects. Approximate monetary equivalents of individual effects should, however, always be indicated when available.

Models are used to study the dispersion and transport of air pollutants. The comparative analysis of the alternatives is performed using straightforward calculations with the standard spread sheet programs for microcomputers. (The calculations are simple enough for being done without any computers, but microcomputers are of significant help.) No sophisticated modelling methods are used.

2. Nature of environmental problems

The location and meteorological conditions of the city area together with the relatively high level of activities producing pollutants (principally traffic, energy production, industry, and small stoves and fireplaces) lead to two types of problems related to air quality:

- occasionally, during particularly adverse weather conditions the level of pollutants may reach values which cause acute health effects after several hours' or several days' exposure,
- in the long term the average level of pollutants is leading to both health and material damages in the city area and its surroundings.

Besides the air quality the following environmental consequences of the various ways of producing electricity are also of significance:

- land use and scenic effects of the power plant itself, oil storage tanks or coal storage area and possibly of expanded port facilities,
- transportation and storage of fly ash and possibly waste from flue gas desulphurization.

Due to the proximity of the sea and several small rivers flowing through the city area the cooling of the power plants does not lead to significant environmental problems.

The chronic health effects are potentially the most severe environmental problems in the city area. Although the electricity production is only a minor contributor to the episodes of high pollution level, care must be taken to prevent any increase in the severity of the pollution episodes. Actually expanding electrification of the city area may help in preventing serious pollution episodes through replacing polluting small stoves by electric cookers.

3. Meteorological conditions and the dispersion of pollutants

The city is located in an area, where the main prevailing seasonal winds are relatively weak. The daily alternating sea and land breezes are thus the winds that most affect the dispersion of pollutants in the city. The sea breeze starts to blow a couple of hours after sunrise, is strongest in the early afternoon and turns into calm a few ours after sunset. Later in the night a weaker land breeze starts to blow in the opposite direction.

The circulation cells of the sea and land breezes affect the dispersion of pollutants. The sea breeze may extend tens of kilometres inland and offshore. The return flow blows from land to sea at a relatively high altitude (1500 - 3000 m). In open areas the wind speed of the sea breeze reaches values of more than 5 m/s. The land breeze is in general weaker and of lesser extent. The altitude of the return flow is about 500 m.

The strong solar radiation and relatively weak winds lead to strong heating of the near-surface air masses. This changes the vertical distribution of the temperature to over-adiabatic and results in the loss of stability and in turbulent air flow. In such circumstances the exhaust plume from the power plant stack gets strongly mixed with the surrounding air and may touch the ground near the source. The concentration of pollutants may occasionally reach high values within about 2-5 km around the source depending on the stack height. These values are, however, usually not high enough to cause by themselves acute health effects. Due to the mixing of air masses the level of pollutants from low level sources is in these situations relatively low. Thus the contribution of power plants with high stacks to the acute health effects is small.

When the surface cools at night the vertical temperature distribution changes and the air masses are stable. Then the exhaust plume from a high stack gets dispersed very slowly and usually touches the ground far from the source (often on the hillsides tens of kilometres away). At these distances the concentrations are already much lower and adverse short term effects are usually absent or weak. Long term effects may, however, be more important.

In the presence of alternating land and sea breeze and in the absence of strong prevailing winds a somewhat complicated pattern of dispersion of pollutants appears. The daytime circulation cell and the relatively strong mixing caused by the instability of the daytime air masses over the land together with the nighttime land breeze may lead to accumulation of polluted air over the sea during the night. When the sea breeze starts to blow in the morning it may bring this polluted air onshore and cause a period of high level of pollutants in the city area.

For quantitative results a more detailed analysis of each particular alternative is necessary. In this analysis the distribution of pollution resulting from each proposed power plant has to be determined. For most purposes the cumulative distributions over long time periods are most significant. In addition it is necessary to consider separately episodes of very high pollution levels appearing during the most unfavorable meteorological conditions.

The long term average pollution levels may be estimated using data on distributions of wind direction and speed, on other meteorological conditions and on the properties of the pollution source. The determination of the amount of emissions is in practice completely separate from the study of the dispersion of pollutants in the atmosphere and their deposition on the ground. The properties of the stack (height and diameter) and the amount and temperature of the flue gases affect, however, the dispersion.

A relatively simple approach that gives adequate results for the long term average levels of air quality in the city area is that applied by the Wisconsin-IIASA team and described in chapter IV A. In the method only the variations in wind speed and vertical stability are taken into account. The main limitations of this method can be identified through the knowledge of the dominant local meteorological conditions, in particular wind patterns. In the present case the most important additional factor to be taken into account is the alternation of sea breeze and land breeze. Taking into account also the stack height an approximate correction to the simpler approach can be estimated. More quantitative results require further measurements to be performed in the city area. Knowledge of the behaviour of the emissions from the older plants may be sufficient for quite precise conclusions.

Theoretical estimation of the frequency and severity of meteorological conditions leading to high pollution episodes is very difficult. The only reliable starting point is in past meteorological observations. Comparison of the altitude of the mixing layer and the effective stack height (including plume rise) allows then one to estimate the significance of the proposed power plant to the pollution level in the particular meteorological conditions being considered. If the pollution episodes are a severe problem, the stack should be high enough to prevent the power plant from contributing to the most severe episodes.

As the city is surrounded by mountains and hills and as the dominant wind pattern is regular, it is possible that the pollution level reaches regularly relatively high values in some areas in the hillsides facing the city. This may happen at a distance, where the concentration of photo-oxidants (in particular ozone) has reached higher values than near the source. In such cases significant damage to the growth of crops may occur. This has to be taken into account in a comprehensive analysis of environmental impacts.

4. Properties of the power plants and typical fuels

The properties of the basic power plant alternatives are given in tables 4.10 and 4.11. The basic plants are not equipped with any emission control devices except for the electrostatic precipitators in the coal fired plant. For the coal fired plant the possibility of adding flue gas desulphurization equipments is included as an alternative. The technical properties of the FGD method considered are given in table 4.12 The choice of the FGD method to be used is a separate problem affected by several local factors. It is, however, assumed here that one method with the properties listed in table 4.12 has been chosen as the method to be used, if FGD is to be applied at all.

Table 4.10 Properties of the oil fired condensing power plant

Net effect (electric)	320 MW
Stack height	200 m
Stack diameter (inside)	4 m
Fuel consumption at 320 MWe	69 m^3/h
Amount of flue gases	830 000 m^3/h (NTP)
Temperature of flue gases	215 °C
Particulate control	none
Flue gas desulphurization	none
Typical fuel	
Type: Heavy fuel oil (viscosity 50°E at 50°C)	
Density	0.97 kg/dm^3
Heating value (lower)	40.5 MJ/kg
Sulphur content	2.8 %
Emissions at nominal power (320 MW_e)	
Sulphur dioxide (SO_2)	3 660 kg/h
Oxides of nitrogen (NO_x)	320 kg/h
Particulates	170 kg/h

Table 4.11. Properties of the coal fired condensing power plant

Number of units	4
Net effect (electric) per unit	250 MW
Thermal effect per unit	600 MW
Stack height	150 m
Stack diameter (inside) (one per unit)	4 m
Fuel consumption at 250 MWe	95 t/h
Amount of flue gases per unit	815 000 m^3/h (NTP)
Temperature of flue gases	130 °C
Particulate control efficiency	99.1 %
Flue gas desulphurization	none
Typical fuel	
Type: Bituminous medium-sulphur coal	
Moisture	10 %
Heating value (lower)	24.6 MJ/kg
Ash content (of dry weight)	14 %
Sulphur content (of dry weight)	2.5 %
Emissions at nominal power (1000 MW_e)	
Sulphur dioxide (SO_2)	14 500 kg/h
Oxides of nitrogen (NO_x)	3 500 kg/h
Particulates	200 kg/h

Table 4.12. Properties of the FGD plant for one coal fired boiler unit (600 MW thermal)

Design sulphur content of fuel	2.5 %
Sulphur removal efficiency (average)	90 %
Method	wet
Chemical	lime stone ($CaCO_3$)
Consumption of chemical ($CaCO_3$)	7 800 kg/h
Cost of chemical (at power station)	$40 /t
Electricity consumption	4.7 MW
Amount of sulphur removed	900 kg(S)/h
Amount of waste produced	10 300 kg/h
<u>Costs:</u>	
Investment (incl. interest during constr.)	40 000 000 $
Fixed costs:	
Capital charges (inter. 10 %, life 15 a)	5 200 000 $/a
Other fixed costs	1 000 000 $/a
Variable costs:	
Chemical	1.25 $/$MWh_e$
Electricity	0.75 $/$MWh_e$
Waste disposal and other costs	0.40 $/$MWh_e$
Combined costs for capacity utilization of 5 200 h/a	7.15 $/$MWh_e$
Corresponding cost per sulphur removed	2 000 $/t(S)

5. Assessment of the alternatives

A typical feature of most short or medium term planning problems for electricity production is that the number of basic alternatives is fairly small, but a large number of variants can be presented of each basic alternative. The relative assessment of the alternatives includes then two distinct stages: comparison of the basic alternatives and comparison of the variants of one basic alternative at the time.

Usually it is most convenient to start with a preliminary comparison of the basic alternatives; this may allow dropping one or more of them from more detailed analysis. Next a nearly optimal variant of each basic alternative should be selected for the final choice between the basic alternatives. Finally at the detailed planning level the chosen alternative should be assessed carefully to obtain the best solution taking into account economic aspects, properties of the energy system, and the environmental factors. In the presentation of the case study we cannot go through all these steps. Instead, we outline a comparison of a few alternatives at a level, which corresponds most closely to the first step, but contains some features of the later steps as well.

In Table 4.13 a list of factors taken into account in the case study is given and comments related to their quantifiability are given. In a comparison one should always remember that quantifiability is not a measure of importance, i.e. nonquantifiable, even intangible damages are often among the most important. On the other hand one cannot give arbitrarily large weight to nonquantified factors as this would also lead to biased decisions. In the present case the following chain of considerations can be used:

a) The power plant should not contribute to acute health effects. This requirement can be satisfied well enough in several ways:
   - building the power plant outside the city area,
   - using filters and flue gas desulphurization, or
   - using high stacks (150 - 200 m) and in case of coal electrostatic precipitators.

b) Calculate the emissions and other quantitative environmentally significant properties of each power plant alternative.

c) Estimate the damages of SO_2 emissions on health (chronic effects), crops, buildings and materials for each alternative. Give them in monetary terms whenever possible. In other cases give a rough guideline to compare effects not given in monetary terms units to each other and to monetary units. This step is to be based on results of step 2 and on data on population densities, location of buildings and other valuable structures and on information on agriculture in the most affected areas. Other areas can be taken into account using rough average values for population and economic activities.

d) List and describe other potentially important environmental consequences and whatever can be said about their magnitude and information.

e) Calculate the direct costs of each alternative and their economic value as part of the electricity network taking into account the need for reserve and peaking power and the reliability of the alternative.

As the comparison includes monetary valued, other quantitative as well as difficult-to-quantify factors, which may all be important, the analyst can give a direct recommendation only in an exceptionally clear case. Otherwise the decision must be left to political decision makers or politically responsible governmental officials.

Here we do not present conclusions for a specific case, as they might rather be misleading than useful, when the approach is used in a practical situation. We do not either give coefficients that can be used in calculating the detriments due to a particular amount of pollutants or a particular level of air pollution. This is, because a considerable amount of discussion should then be included on the accuracy, reliability, and other factors affecting the proper way of using these coefficients. Information on the coefficients is presented ,e.g., in other publications of the Energy Report Series (ERS) of UNEP. Some coefficients used in a particular model setting are also given in section A. They should only be used in a practical planning problem, if proper care is taken to check their applicability to the situation studied.

Table 4.13. Quantifiability of economic and environmental factors

	Quantifiability	Remarks
<u>Economic factors:</u>		
Cost of power plant	Quantifiable in monetary units. Presented usually as levelized annual costs in comparison of energy production costs.	Financing arrangements and need of foreign currencies are also of central importance.
Network construction costs	Quantifiable in monetary units. (See above)	Differs significantly only if the power plant is situated outside the city area.
Fuel costs and costs of operation	Quantifiable in monetary units	Domestic fuels may be preferred even at significantly higher cost.
Costs of environmental protection measures	Quantifiable in monetary units. Contains both investment and operational costs.	Typically includes: plant investments, chemicals for flue gas desulphurization and operational costs.
<u>Costs related to energy system</u>		
Peaking and reserve power	Quantifiable in monetary units.	Includes both expenditure used to improve reliability and losses due to black-outs.
Transmission losses and costs	Quantifiable in monetary units.	Depends on the structure of national network.
<u>Environmental factors</u>		
Emissions of pollutants	Quantifiable in physical units.	An intermediary quantity, used to estimate damages, many of which are detailed below.

Air quality in city area (long term average)	Quantifiable in physical units using meteorological dispersion models.	As above
Air quality in city area (pollution episodes)	Frequencies can be estimated. The most severe episodes are very difficult to estimate.	An intermediary quantity related to acute health effects (see below).
Air quality and deposition of chemical pollutants outside the city area	Approximately quantifiable in physical units. The chemical transformation during the transport insufficiently known.	An intermediate quantity related principally to losses to crops, forests and aquatic ecosystems.
Releases of heat to water or air	Quantifiable in physical terms.	Insignificant damages in the present case.
Acute health effects	Stochastic risk quantifiable with poor accuracy. Monetary equivalence not objectively quantifiable.	Due to stochastic nature of pollution episodes good accuracy is not obtainable even with very good knowledge of contributing factors.
Chronic health effects	Quantifiable with poor accuracy. Monetary equivalence not objectively quantifiable.	Occur mainly in the city area, but possibly also outside.
Damage to buildings and structures	Quantifiable with poor accuracy, partly also in monetary units.	Damage to historical monuments etc. most difficult to value.
Damage to crops	Partly quantifiable, then usually also in monetary units, partly unknown at present.	Effects of ozone best known. Damages can be alleviated through change of crops.
Damage to forests	Only very rough limits for order of magnitude can be given.	Even the relative importance of different pollutants is unknown, but the potential damage is very large in many areas.

Damage to aquatic eco-systems	Risk levels of acid deposition are known. Potential damage can be estimated based on present value of fish etc. in rivers and lakes.	Often due to international transport of acids (SO_2, SO_3, NO_x) in atmosphere.
Land use, scenic values etc.	Easily described for a particular project. Difficult to value in monetary units.	Losses related to land use are not necessarily equal to the price of land area.
<u>Other factors</u>		
Occupational health effects and accidents	Quantifiable from statistical data.	Mining activities etc. are left outside the case study.
Employment and other social effects	Gross effects quantifiable, quantification of net effects compared to alternative choices is more difficult.	Overall effect may be positive or negative, and is usually more important if the plant is situated outside the city area.

C. SULPHUR EMISSIONS FROM ENERGY PRODUCTION IN A DEVELOPED COUNTRY

1. INTRODUCTION

The emissions of sulphur oxides (mainly sulphur dioxide, SO_2) have been recognized as one of the most serious causes of environmental damage in Europe and Northern America. Therefore in many countries national policies have been introduced to cut the emissions to a lower level than at present. Sulphur dioxide as well as SO_3 and sulphates formed from SO_2 in the atmosphere are transported long distances in the atmosphere and cause thus an international environmental problem. Consequently, an international agreement has been signed by a number of countries requiring the participating countries to reduce their sulphuric emissions by at least 30 % from the level of 1980 before the year 1993. In many countries, including Finland, with which this case study will deal. More demanding goals have been proposed or set as national policies.

The long distance transport of sulphur oxides means that the total amount of emissions is a most significant quantity. This is contrary to locally deposited pollutant, where one should consider each source of pollution separately in its local settings. The long distance transport does, however, not mean that the air pollution and sulphuric depositions would be evenly distributed over the whole affected area.

From the point of view of formulating environmental policy, the international agreements and the significance of the total amount of emissions make it meaningful to formulate guidelines that concentrate on reducing the total emissions with lowest achievable costs for the national economy. This is one approach chosen in studying, how the sulphuric emissions should be reduced in Finland.

The optimal way of reducing the sulphuric emissions should, however, take into account also the actual damage caused by the domestic sulphur emissions on health, lakes, forests, and materials. These damages do not depend on the total amount emitted only, but also on the locations and stack heights of the sources. The estimation of the damages is, however, beset with great difficulties arising from the lack of knowledge on the impact some particular level of pollution or deposition will
An intermediate analysis estimating the average ground level concentration and deposition of sulphates (including sulphuric acid) in each part of the country, may thus be the most useful quantitative analysis achievable today.

In this section brief description will be given of some approaches used in analysing the policy options for limiting sulphur emissions that arise from energy production in Finland.

2. Limiting the total amount of sulphuric emissions

As in most countries, energy production is the largest source of sulphuric emissions in Finland, although the process industry, in particular pulp manufacture, releases about 40 % of the total emissions. The emissions due to process industry are going to be reduced through renewal of industrial processes and improved methods for retaining the sulphur containing chemicals in the process. The costs of speeding significantly up the reduction of sulphur emissions from the process industry appear to be higher than the costs of reducing the emissions from energy production. Thus the energy production offers the best opportunities to affect the amount of sulphur emissions through policy decisions.

The oil products (dominantly heavy heating oil) and oil refineries are presently (1984 data) responsible for about 40 % of the total sulphur emissions. This contribution has been rapidly decreasing due to diminishing consumption of oil in power plants. Simultaneously the consumption of coal has remained at a relatively low level thanks to good availability of hydro and nuclear power. In the coming years the need for coal fired electricity production is going to increase and contribute to the sulphur emissions. None of the existing power plants has FGD equipment (decision on the first has been made), but the sulphur content of coal used in Finland is on the average about 1 % and thus not particularly high.

A more detailed understanding of the expected development of the sulphur emissions has been obtained through a detailed analysis of the future energy system. In this analysis all large production units have been handled individually and the smaller units as subsets corresponding to the location and the type of energy produced. The total expected emissions have then been determined on the basis of the energy produced by each unit or subset of small units, the fuel mix of the unit or subset, sulphur content of each fuel, and a technical coefficient describing the share of sulphur emitted in flue gases.

All the above calculations have been performed using personal computer and commercial spreadsheet program. Working with these technical aids is very straightforward, all the problems being related to the collection of data and building up the energy production scenario for years 1990 and 1995 considered in the study.

The above analysis of expected developments can then be used as a starting point for analyzing policy options. The costs of different ways of reducing the sulphur emissions can be determined and fed to the spreadsheet calculational systems. The technical options include:

- adding FGD equipment to each large unit,
- replacing future conventional units by less polluting alternative technologies, e.g. fluidized bed combustion,
- switching fuels, e.g. from coal to natural gas,
- importing fuels with lover sulphur content,
- cleaning fuels.

For each option one should specify the limits of the technically and economically achievable reductions in emissions as well as the cost per unit of sulphur removed from the emissions. The capital costs and operational costs are given separately.

The policy options include

- limiting further the concentration of pollutants in flue gases,
- limiting the emissions per unit of energy produced,
- requiring FGD for large units,
- limiting the sulphur content of the fuels,
- introducing taxation dependent on the amount of emissions.

Each type of policy option can be varied by changing the limits on pollutants and set of power plants, to which each type of limitation applies.

Based on the above data policy options can be analyzed as follows:

- determine the consequences of the policy for each option for reducing the emissions,
- use the spreadsheet system to calculate the resulting reductions in total emissions and the resulting costs due to implementing the policy.

One can easily proceed to compare many different options. The more advanced features of the spreadsheet programs can be used to automatize a large fraction of the work: The consequences of the policy can be determined automatically using conditional clauses in the spreadsheet. This is particularly useful for alternatives that differ only in quantitative details.

The detailed description of the energy system on the unit level allows one also to check, which energy producers are going to be economically affected. This helps in deciding, whether the economic burden should be redistributed in some way.

3. Regional analysis of emissions and damages

Indicating the location of each individually described unit by geographical coordinates and using a sufficiently fine grid in defining the subclasses of the remaining units it is possible to determine precisely the areal distribution of emissions. Using information on stack heights, detailed meteorological data and dispersion models one may then construct precise maps for the average concentration of pollutants from domestic sources. In line with the present analysis it is for many purposes sufficient to perform a simpler analysis that can be completed using the same spreadsheet program as in the earlier steps.

This approximate regional analysis is based on the following steps:

1. Divide the country into a number of distinct areas.
2. Determine and tabulate transport coefficients that indicate, which average fraction of emissions in area i is deposited in area j and which ground level concentration results in area j from a unit emission in area i. This is to be done for all pairs i and j. No further knowledge on the dispersion is to be used

in the analysis. (It is, however, possible to use different coefficients for different stack heights.)

3. Determine the total emissions in each area (possibly divided according to stack height).
4. Calculate the deposition and ground level concentration in each area using coefficients from step 2 and emissions from step 3.

Steps 3 and 4 are to be repeated for each scenario for energy production and pollution control.

As stated in the introduction to this chapter it is at present not possible to estimate with reasonable accuracy the damages due to such levels of SO_2 concentration and acid deposition that are likely to occur in Finland. It is, however, known that certain lakes are particularly susceptible to acidification. It is also apparent that certain increase in the SO_2 concentration is more harmful in areas, which are more heavily affected by other sources of pollution. Thus one can with fair justification make comparisons between alternatives that differ mainly with respect to the location of the sources. It may also be prudent to set more strict limitations on emissions in some areas than in the others.

CHAPTER V

ENERGY-ENVIRONMENT OPTIMIZATION MODELS

A. INTRODUCTION

From the discussion in the last two chapters it could be concluded that in spite of the fact that several methods and tools are available to incorporate the environmental factors into energy planning and decision-making processes, energy-environment models with the exception of few cases have not yet proven themselves as one of the most efficient and commonly used tool in energy planning. The reasons have been extensively discussed in chapter III. Again with the exception of few cases, the models available have generally addressed themselves directly to the most complicated issue in environmental assessment and management, via, the comparative assessment of the environmental impacts of energy production and use and their cost/benefit analysis.

Altough it is possible to collect data on the residuals, emissions and health hazards of energy sources and it would be very useful to consult and use them in the energy planning process, the first phase of this study on the comparative assessment has demonstrated that these data alone could not be used to undertake a complete comparison among energy sources in all cases. This was mainly because the environmental impacts of the different energy sources vary in magnitude, duration, nature and even in space, i.e., in the place of their occurance. For this reason it was necessary to undertake a separate study on the cost/benefit analysis of the environmental impacts of energy sources, which was the subject of phase II of the study on the comparative assessment.

This latter study on the cost/benefit analysis enabled us to go one step further and to estimate and compare in several pratical cases the costs and benefits of those environmental impacts of energy sources which we could only compare, in phase I, their emissions, residual and the health hazards. It also provided us, using illustrated examples and practical cases, with several methods to undertake the cost/benefit analysis.

The two studies have also assisted in pointing out the serious gaps in information on the environmental impacts of the production and use of energy and the difficulty in undertaking a comprehensive cost/benefit analysis. An extremely important result of both studies was that the environmental impacts of the production and use of energy is very much site specific. A coal power plant built in an industirial country like FRG or USA dos necessarily have the same environmental impacts as a similar plant built in a developing country like Algeria or Brazil. Similarly a nuclear power plant built in a densely populate country like the Netherlands would hardly have the same environmental risks as a similar one built in a sparely populated country as Finland or Kenya and so on.

It was also felt that in spite of the important guidance the two studies offer to decision-makers, planners and scientists there still exists a need of developing that "yard stick" which the planners and decision makers can use to incorporate the environmental factor into their final planning and decision-making processes and allow them to take into account the characteristics of each site. Hence was the decision of undertake this study.

In this chapter a practical approach together with an example will be given on a selected technique to incorporate the environmental factor into an existing energy optimization model.

B. THE NECESSARY CHAIN OF ACTIONS AND ACTIVITIES

The energy-environment optimization models to be discussed in this chapter are far from being an overall complex energy-environment model as the one developed by IIASA (see IV.A). They are meant to be used as a tool to incorporate the environmental factor into energy decision making process rather than a substitute to a planner or a decisionmaker. Hence there is a chain of actions and activities to be taken and undertaken before being able to use effectively the optimization models.

Two important human decisions have to be made before proceeding with the optimization model.*) The first, on the environment line concerning the accepted levels of risk and pollution of the energy sources under consideration. The second, on the energy line concerning the scenarios to be fed to the model. The chain of actions and activities is simplified in fig. 5.1. The energy and environmental lines are merged together before going to the optimization model. The interactions between the different stages in the two lines is not shown to avoid complicating the diagramme.

Brief explanations of the different activities and data preparation processes is given below. It goes without saying that several other models and mathematical codes could be used at the stages preceeding the optimization process. However, discussion of these models and codes will not be considered below.

1. The environment line

a) Collection of data on the residuals, emissions and health hazards of energy sources should concentrate only on these energy sources under consideration which are to be fixed in consultation with people working on the energy line. International literatures, as UNEP's and OECD publications, as well as national measurements should be consulted. In other words this step may be called risk identification.

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*) It is also possible, as will be explained later, to compare through an iteration process the economic implications of several decisions before making the final decision.

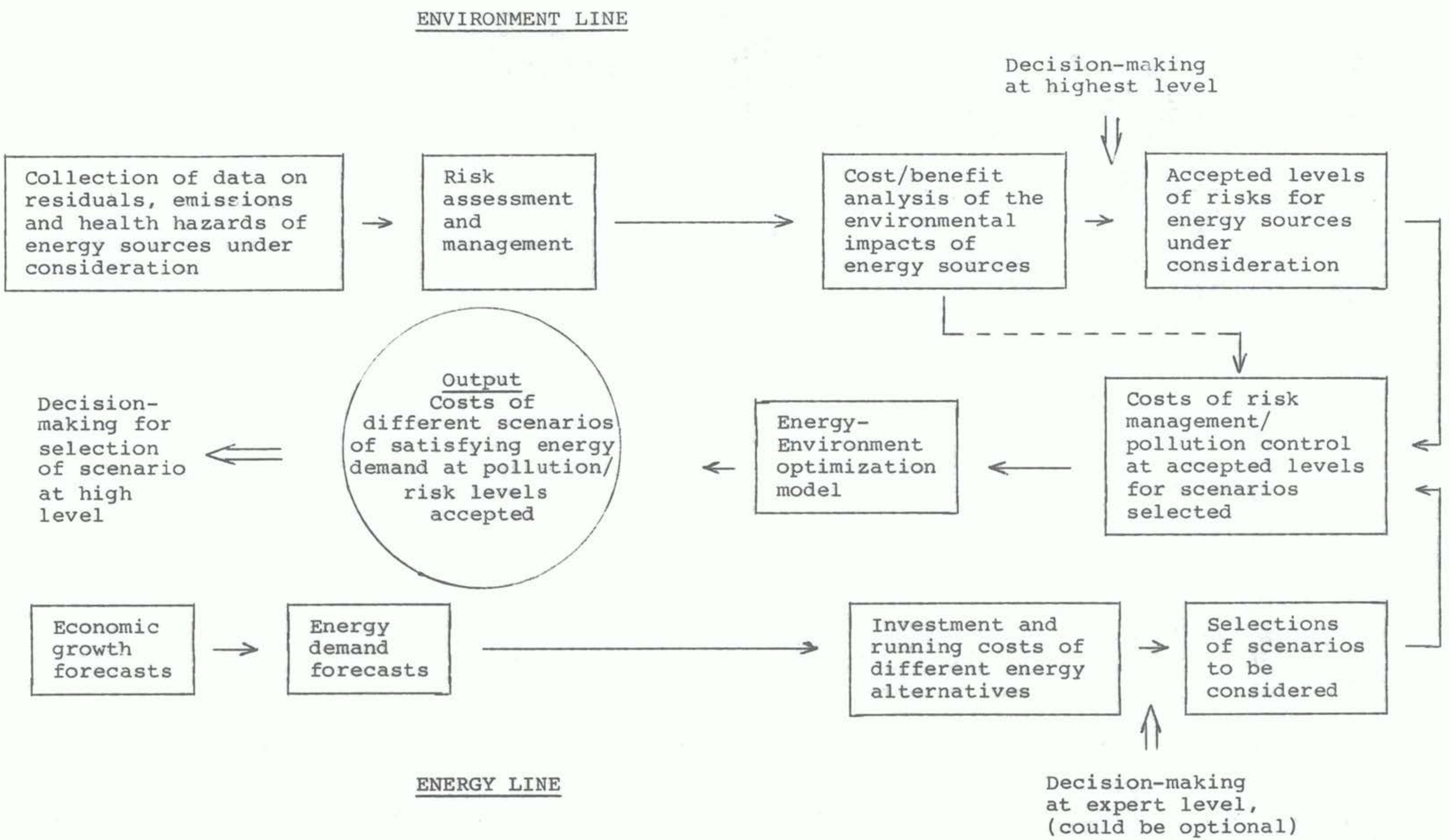

Fig. 5.1 Merging Energy & Environment lines into the Energy Environment Optimization Model.

Source: ElMahgary 1986

b) Thr next step is an analysis on risk assessment and management which embraces both the determination of levels of risk and the social evaluation of the risks. Risk determination consists of estimating the likelihood and magnitude of the occurance of the risks which were already identified in the preceeding step on collection of data. Risk evaluation measures the acceptable levels of societal risk and the methods of avoiding them. Several sources could be consulted in this respect e.g. UNEP 1985 a, UNEP/IAEA/WHO 1984 and UNEP/IAEA/WHO 1981.

c) The next procedure consists of undertaking a cost/benefit analysis of the environmental impacts of those energy sources to be considered in the optimization. Its purpose is not, to assign monetary value to all the impacts, but rather to concentrate on giving estimates of the costs of controlling pollution or decreasing a certain environmental risk. The benefits of these actions should be then described in terms of money-saved, mortality, morbidity or deterioration of natural resources or historical monuments which would be occured in case this pollution control/risk management actions were not taken. The purpose of this step is to provide the decision maker with the information which he needs in order to decide upon the level of risk which the society would accept. Since this is an extremely important and difficult decision it should be taken at the highest level in view of its political implications. In some countries this is entrusted to the Parliament, in others to the Cabinet or a Ministery. Among the different background information needed, a risk/cost diagramme for each risk in question (acid rain, radiation control, particulate control, etc..) would certainly be helpful (fig. 5.2).

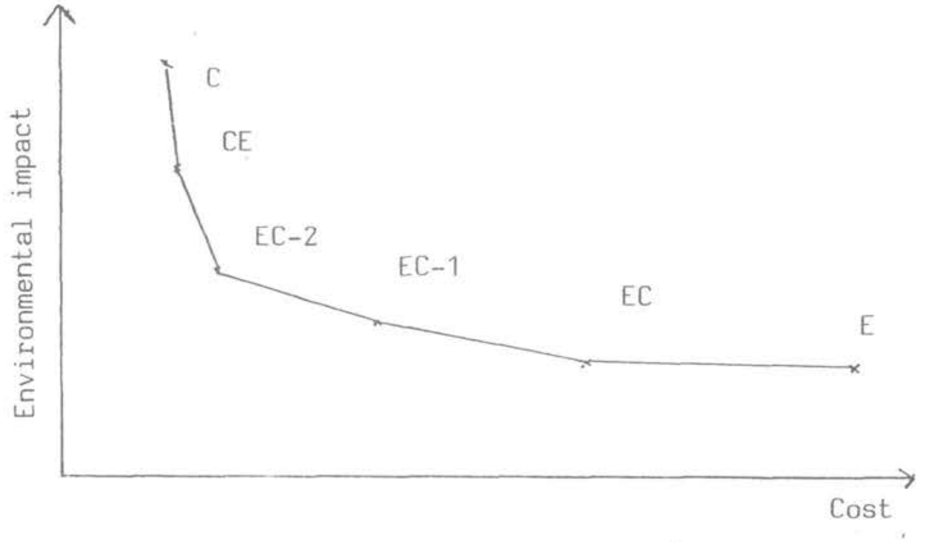

Fig. 5.2. Risk/costs relationship.
For details please refer to UNEP (1985b)

d) Next we come to the decision-making stage. With the help of the information collected and prepared in the preceeding stages decision/decisions should be made as to the levels of risk to be accepted by the society. For a fossil power plant one would expect a decision on the efficiency of scrubbing particulates, sulphur dioxide (SO_2), maximum temperature of thermal charges, etc.. For a nuclear power plant one might expect an upper limit for the risk of nuclear plants including radioactivity releases both at normal operation and in case of an accident, etc. These decisions have serious societal and economic effects. The societal effects should be analysed and studied in details. The economic effects would be studied through the optimizing models. This is anohter advantage of the optimizing models, viz, they could be used in the making of decisions about the levels of accepted risk. The planner can assume certain values and study their economic implications.

e) After deciding upon the accepted levels of risk of the different energy sources it is not difficult to estimate, using information from the cost/benefit analysis undertaken, the corresponding costs of risk management and pollution control. This information are to be fed to the model as input data.

2. Energy line

The stages of preparing the information on the energy line are the straightforward procedures of data collection and preparation for an energy optimization model (please refer to chapter II). The decision on the selection of scenarios is usually made at the expert level.

C. ENERGY-ENVIRONMENT OPTIMIZATION MODEL

The main emphasize will be, as in the preceeding chapters, on energy optimization models for the electric power system. This is because the electric power system is usually the most important energy producing system in a given country and also, as has been demonstrated in phase I of the study on the comparative assesment, because the methods used here could be extended to other end uses as heat generation and mechanical energy (UNEP 1985 a).

Several optimization models have been developed and are beings used successfully in energy planning all-over the world. A few of them were discussed in chapter II. Many of these models could be adopted to include the environmental factor.

The main conditions that the model should satisfy are:

a) The models should be simple in construction and easy to use. This will faciliate the integration of the environment factor into the model.

b) The model should be comprehensive and should include the optimization of thermal as well as hydro and other (renewable energy) power plants.

c) It should be possible to operate the model on more than one level, e.g., on national as well as on regional levels.

d) Both reliability and accuracy of the model should be known. This implies earlier testing of the model.

e) The model should provide means to include a technique to accomodate uncertainties, perferably in the form of probabilistic functions.

f) The model should be suitable to be used as sub-routine to other models/codes (which funtions, e.g., are those given in the blocks of fig. 5.1) to form and overall general energy-environment model if it is so desired.

g) The model should optimize at the same time the operation of the power plants and the distribution of the storable hydropower throughout the year.

h) The model should enable the determination of the main configuration of the optimum expansion of the power system within established environmental, technical and economic constraints.

1. The outlines of a suitable energy optimization model.

The conditions listed above could be found in a number of models. One of them viz, ESOREM, was developed within the frame of a Joint Finnish/Swedish Project (ElMahgary and Larsson 1976). The main features of the model and the possible modifications to be made in order to include the environment factor into the optimization process will be briefly discussed in the following.

a) Main features of the ESOREM

The representation chosen for the production system is shown in figure 5.3. The total water inflow is divided into storable and nonstrorable hydro power. The latter must be used instantaneously when it is available, or it will be lost, whereas the former could be stored to be used at peak load. A nuclear layer which consists of back-pressure and condensing plants can be specified. After that follows the fossil layer which, in turn, might consist of numerous sublayers; e.g. back-pressure industrial, back-pressure heating, fossil base-load plants and fossil intermediate load plants. The hydro system is characterized by constraints with respect to the minimum amount of flow to be maintained in the river throughout the year. Operation constraints on the thermal plants are given in the form of availability factors at different time segments of the year. Up to 13 different values for the availability could be given to each plant group per year.

The transport and handling cost are, included in the running costs of each plant. The representations of the system through time is approximated by modelling the system operation in "snapshot" years, and interpolating for the intervening years.

a) Optimum operation of the electrical system

The detailed operation of the plants of the system is determined by minimizing the following objective function:

minimize the sum of the running costs i.e.,

$$cr_k = \sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij} P_i h_j cr_i \qquad (5.1)$$

where

cr_i the running costs of plant group i

cr_k the total running costs in the year type k

i plant group

j time segment of the year

X_{ij} level of operation of plant group i in time segment j
$0 \leq X_{ij} \leq a_{ij} \leq 1$

a_{ij} availability of plant group i in time segment j

P_i power of plant group i

h_j number of hours in time segment j

The minimization is performed subject to the following constraints:

- Total energy demand for each time segment of the year should be satisfied
- Hydro energy production should, in each time segment, be greater than the minimum run-of-river.
- At the final runs the level of the water reservoir should in each period be within the given limits.

b) Optimum plant mix of the electric system

In order to determine the optimum plant mix the capital costs should be included in equation (5.1). The objective function will then read;

minimize

$$C_{Eg} = \sum_{\tau=1}^{T} r^{-\tau} \{\sum_{k=1}^{K} w_k \; cr_k + \sum_{i=1}^{I} C_i \; P_i\} \qquad (5.2)$$

where

C_{Eg} total costs

$r^{-\tau}$ discount factor

w_k weight factor for year type k

C_i capital costs of plant i

τ year considered in the study

T number of years included in the study

In order to avoid complicating the optimizing process with data and variables that are not directly influencing the power system, the expansion of fossil industrial and heating back-pressure plants is determined according to known expansion plans.

The year is divided into 13 equal time-segments. The maximum and minimum power demand in each time segment is given. The load duration curve in each time segment is approximated by a linear form, thus the energy demand in each time segment will be represented by a trapezoid. The model starts to satisfy the demand using all nonstorable hydro power taking into account that the minimum run-of-river, should not be outstripped. There-after, the the model continues to satisfy the demand using thermal plants and starting with the plant or plant group of minimum running costs until the total energy demand of the time segment under consideration is satisfied. The model considers then the next time segment until the demand of the whole year is satisfied using non-storable hydro-power, thermal power and rational plants, if necessary. After that, the program begins to substitute rational and peak load plants by storable hydro power starting with the time segment where the production of the peakpower plants is maximum. At the same time the reservoir level is adjusted and necesary modification in the electricity production of the different layers in other time segments are carried out.

2. Incorporation of the environmental factor into energy optimization models

In order to incorporate the environmental factor into the energy optimization process it is necessary to introduce new term into the objective function, and the constraints if necessary. Having decided upon the accepted level of risk for the different energy system the costs of the technology/actions needed to ensure that level have to be estimated. In general there will be additional terms to equation 5.2 which will read.

minimize

$$C_{Eg} + C_{Ev} = \sum_{\tau=1}^{T} r^{-\tau} \left\{ \sum_{k=1}^{K} N_k \,(er_k + er_{Ev}) + \sum_{i=1}^{I} (C_i + C_{Ev})\, P_i \right\}$$

where C_{Ev}, cr_{Ev}, Ci_{Ev} refer to the total, running and investment costs of the technology or the actions needed to be used/taken to ensure that the environmental conditions will be within the levels accepted.

In the case a of coal plant, e.g., Cr_{Ev} and Ci_{Ev} will directly be equal to the additional running and investment costs of introducing e.g. the Sulphur Dioxide/particulates, scrubbing technologies if a decision is made to control these pollutants. Again in the case of a nuclear power plant the actions needed to decrease the risk of, e.g., a major reactor accident to a certain level, could be analysed into investement and running costs which could be then inserted to equation 5.3) and so on.

Costs of the pollution control/risk management as could be seen from the ojective function has not to be the same for different plants. Hence the level of pollution control could be site specific if it is so desired. This gives a considerable flexibility in connection with environment management and policy.

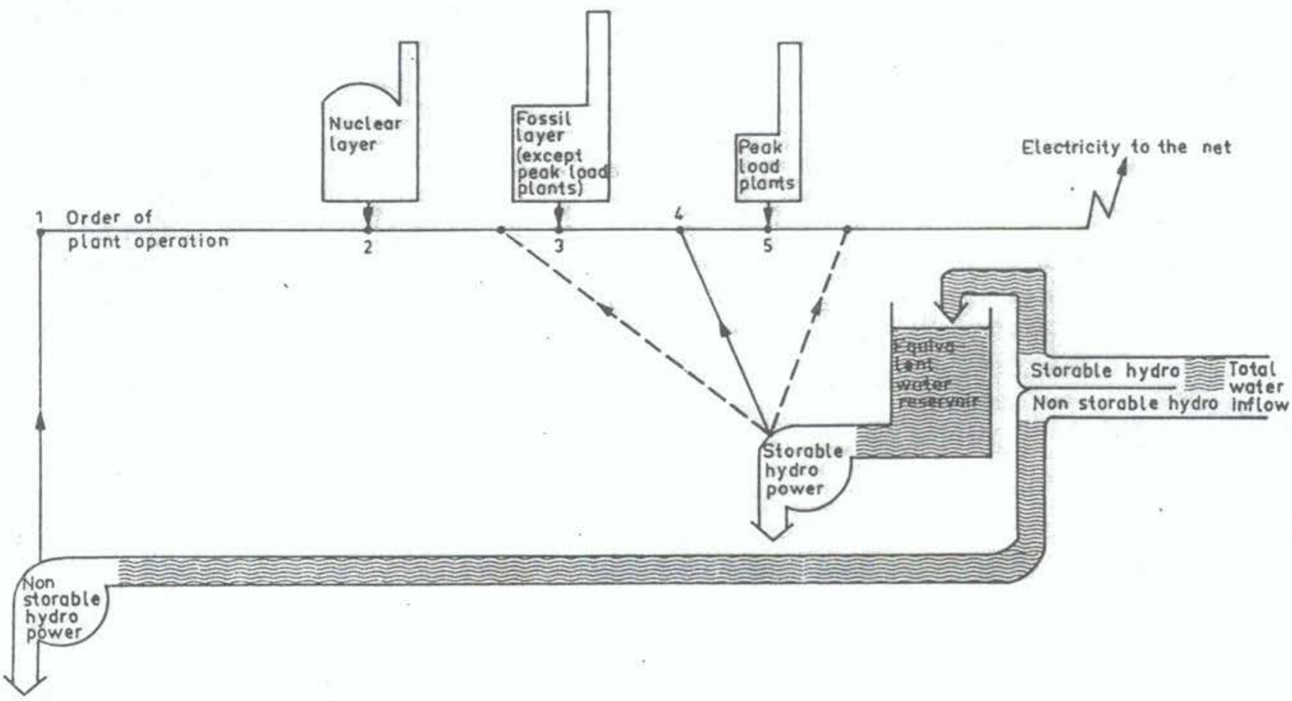

Figure 5.3. Simplified representation of the electrical system

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