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Enhanced Electricity System Analysis For Decision Making — A Reference Book

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FOREWORD

The objective of electricity system analysis in support of decision making is to provide comparative assessment results upon which relevant policy choices between alternative technology options and supply strategies can be based. This reference book offers analysts, planners and decision makers documented information on enhanced approaches to electricity system analysis, that can assist in achieving this objective. The book describes the main elements of comprehensive electricity system analysis and outlines an advanced integrated analysis and decision making framework for the electric power sector. Emphasis is placed on mechanisms for building consensus between interested and affected parties (IAPs), and on aspects of planning that go beyond the traditional economic optimisation approach.

The scope and contents of the book cover the topics to be addressed in decision making for the power sector and the process of integrating economic, social, health and environmental aspects in the comparative assessment of alternative options and strategies. The book describes and discusses overall frameworks, processes and state of the art methods and techniques available to analysts and planners for carrying out comparative assessment studies, in order to provide sound information to decision makers.

This reference book is published as part of a series of technical reports and documents prepared in the framework of the inter-agency joint project (DECADES) on databases and methodologies for comparative assessment of different energy sources for electricity generation.

The overall objective of the DECADES project is to enhance capabilities for incorporating economic, social, health and environmental issues in the comparative assessment of electricity generation options and strategies in the process of decision making for the power sector. The project, established in 1992, is carried out jointly by the European Commission (EC), the Economic and Social Commission for Asia and the Pacific (ESCAP), the International Atomic Energy Agency (IAEA), the International Bank for Reconstruction and Development (IBRD/World Bank), the International Institute for Applied Systems Analysis (IIASA), the Nuclear Energy Agency of the OECD (OECD/NEA), the Organization of Petroleum Exporting Countries (OPEC), the United Nations Industrial Development Organization (UNIDO) and the World Meteorological Organization (WMO). The main elements and achievements of the DECADES project are described in the different chapters of this book. Additional details are provided in the chapter references and in the bibliography.

The Joint Steering Committee for the DECADES project hopes that this book will contribute to the process of strengthening and improving capabilities for the design and implementation of sustainable strategies in the power sector, in particular in developing countries and countries in transition to market economies. The Secretariat of the Joint Steering Committee would be grateful to receive comments from readers, in order that future editions can be improved.

The reference book has been prepared with the assistance of many contributors, coming from national and international organizations active in the field of electricity system analysis.

The initial drafting of the different chapters and annexes was carried out by highly qualified experts (see the list of contributors to preparation, drafting and review) who served as leading or contributing authors, drawing from their experience and know-how on the subject matter. The book could not have been completed without the contributions of this initial drafting team.

The draft chapters prepared by the lead authors and contributors were harmonised and technically edited jointly by staff members of: the IAEA Planning and Economic Studies Section, the Nuclear Development Division of the OECD Nuclear Energy Agency, and the Industry and Energy Department of the World Bank (IBRD). The final version of the book was prepared by L.L. Bennett (formerly Head of the IAEA Planning and Economic Studies Section, now retired) under a contract with the IAEA. The IAEA officer responsible for the book was I.F. Vladu of the Planning and Economic Studies Section, Department of Nuclear Energy.

Participants in the two consultancies and the two advisory group meetings convened by the IAEA in 1994 and 1995 (see the list of contributors to preparation, drafting and review) provided valuable guidance and assistance in designing the book, ensuring its consistency and enhancing its coherence and completeness.

The important contributions made by many experts who provided background information on specific issues and topics, and/or reviewed and revised portions of the manuscript, are gratefully acknowledged also.

Finally, a special acknowledgement is given to the senior experts who kindly accepted the task of peer reviewing the reference book as it neared completion (see the list of contributors to preparation, drafting and review). The advice given by these experts on ways to improve the presentation was very valuable in the process of preparing the final text of the book for publication.

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CHAPTER 1

INTRODUCTION

The increasing awareness of social, health and environmental impacts of human activities has broadened the range of issues that need to be addressed by analysts and taken into account by decision makers in the power sector. The concept of sustainable development calls for integrating social equity and ecological equilibrium together with economic criteria and technical parameters in a comprehensive and coherent electricity system analysis framework. The enhanced approach proposed and presented in this Reference Book aims towards identifying feasible development paths in order to assist in implementing sustainable energy strategies. The approach can assist also in identifying planning risks (e.g. owing to uncertainties) and competitive opportunities for electric utilities, independent power producers (IPPs) or the power sector as a whole.

Most of the individual elements needed for an integrated approach to electricity system analysis in support of decision making have been described comprehensively in the literature. There are also a number of books describing methodologies and techniques for economic optimisation, environmental impact assessment, probabilistic risk assessment, and assessment and valuation of externalities for electricity generation projects and strategies. Analytical models and computer tools that have been developed and implemented for such studies are well documented.

However, most of the published literature tends to focus on techniques for assessing and comparing specific factors (e.g. direct costs, health and environmental impacts, externalities) related to different options and strategies for the power sector. This book, on the other hand, attempts to provide a ***comprehensive description of the overall process*** for addressing economic factors, social aspects, routine and severe accident effects, health and environmental impacts and externalities in an integrated framework, and for incorporating the different issues into an enhanced decision making framework. The approach described is intended to go beyond traditional planning procedures, by taking into account the emergence of new issues and priorities for the power sector, such as deregulation, privatisation and concerns about the global environment. The book emphasises the process of building consensus between interested and affected parties (IAPs) and decision makers.

This book is designed to be essentially an introduction to enhanced electricity system analysis. Therefore, it provides an overview of the different elements, levels and actors involved within an integrated framework for decision making. However, the book provides only brief summary descriptions of methodologies, models and tools that can be used for the analysis of the specific elements of the integrated framework. The reader is invited to refer to the references and bibliography for more information on such tools.

1.1. History of the book

This reference book is one of the outcomes of the inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES) [1]. The overall objective of the DECADES project is to enhance the capabilities for comparative assessment of electricity generation options and strategies through providing a framework and tools, i.e. data bases and analytical models, for assessing economic, social, health and environmental aspects and integrating these aspects in the decision making process for the power sector.

Within the DECADES project, a group of experts had prepared a working document on computerised tools for comparative assessment of electricity generation options and strategies. That document constituted a catalogue describing state-of-the-art computer tools that can be used by analysts and policy makers for assessing and comparing alternative electricity system expansion paths. The experts who had contributed to that document pointed out the need to provide, in a book that could serve as a reference, an overview of the overall methodological approach to integrated electricity system analysis for the purpose of decision making, and recommended to undertake the preparation of such a reference book within the framework of the DECADES project. Preparation of this reference book was undertaken in response to that recommendation.

The present reference book complements other publications from international organisations on electricity system analysis and planning and environmental impact assessment, in particular, the IAEA guidebook [2] on electricity system expansion planning, which focuses on the classic least cost planning approach, the IAEA documents on comparative assessment of health and environmental impacts of electrical energy systems [3, 4, 5, 6, 7, 8], and the World Bank reports on environmental impact assessment [9, 10, 11].

This reference book has been prepared by a group of experts from national and international organisations, who designed its overall structure, collected the background information and drafted the different chapters. The IAEA, the OECD/NEA and the World Bank were responsible jointly for harmonising and finalising the book in its present form.

1.2. Objective and target audience

The **objective** of the reference book is to provide state-of-the-art and documented information on enhanced electricity system analysis in support of decision making in the power sector. It highlights the main factors to be considered for assessing and comparing alternative options and strategies for supplying electricity services. The book outlines an overall framework for integrating technical, economic, social, health and environmental aspects in the decision making process. Moreover, it highlights ways and means to involve IAPs in the process, recognising their different concerns, view points and priorities.

The **target audience** of the book is primarily senior power sector analysts and planners in governmental agencies, international organisations, electric utilities and independent power producers (IPPs). Also, all the parties involved in and affected by policies in the power sector, including associations of consumers and non-governmental organisations, will find the book a source of general information on the characteristics and potential impacts of different fuel cycles and technologies for electricity generation.

The book is of particular interest for analysts and decision makers faced with a need to take decisions on electricity system expansion under stringent economic and/or environmental constraints. Therefore, it is expected to be especially relevant for developing countries where rapidly growing electricity demand has to be met with limited financing capabilities, while minimising environmental burdens. Enhanced electricity system analysis is of high relevance also for countries in transition to market economy, where economic and environmental protection criteria have to be addressed within newly established market-oriented policy making frameworks. However, the issues addressed in the book and the process, framework and methods described are applicable in all countries. The adoption of this approach in support of decision making at the national, regional and electricity utility levels could promote the implementation of sustainable strategies for meeting electricity service requirements world-wide.

In this connection, the book will be used by the IAEA and other international organisations in training courses, workshops and seminars on energy, electricity, health and the environment, aiming towards enhancing capabilities for designing and implementing sustainable strategies for supplying electricity services.

1.3. Scope of the book

The book addresses electricity system analysis essentially for the purpose of decision making on medium to long term electricity supply strategies at the national or regional level, rather than at the level of feasibility studies for specific projects. Its scope covers the main aspects to be integrated in the decision making process for the power sector, taking into account the overall economic and energy context as well as social, health and environmental concerns. The approach described for decision support analysis is intended for use in establishing medium and long term strategic plans for the power sector.

Since electricity systems are part of the energy sector, which in turn is part of the whole economy, the book briefly covers issues related to macroeconomics and the energy system as a whole, insofar as the analysis of electricity demand and supply is linked to them.

Given the wide range of objectives, energy needs, natural resource availability and technical and industrial infrastructures prevailing in different countries and regions, the book does not deal with specific situations, but instead focuses on generic features of the analysis and decision making process. Analysts and decision makers should adapt such generic frameworks to specific local and regional conditions when applying them in support of their policy making.

The assessment framework for comparing alternative electricity generation options is based upon the full energy chain (FENCH) approach which incorporates the different steps and levels in energy chains contributing to electricity supply (see Chapter 3). The electricity generation system is built up by combining the various energy chains (fossil, nuclear, renewable) that have been selected as options for meeting future electricity demands. The energy chains include, whenever applicable, primary energy source extraction, fuel processing and transport, fuel conversion, electricity generation, transmission and distribution, pollution control, waste management and disposal, decommissioning of facilities, and rehabilitation of sites. Although, theoretically, the comparative assessment could be based upon life cycle analysis (LCA - see Chapter 3), the full energy chain approach has been adopted in this book because, for the purpose of electricity system analysis, it provides a more than satisfactory estimation of the emissions and residuals, while avoiding the additional complexity of LCA. Comparisons of results from FENCH and LCA studies have shown that there are no significant differences in the emissions and residuals estimated by the two approaches. It should be noted that issues of non-electrical energy uses and demand side management (DSM) often are treated more fully through LCA than by the FENCH approach. However, the FENCH approach can be adapted to cover these issues, by appropriate expansion of the boundaries defining the energy chain limits.

Environmental impact assessment (EIA) includes the estimation of air and water emissions, solid wastes generated and other residuals, e.g. visual intrusion and impacts on biodiversity. Local, regional and global impacts resulting from electricity generation and use are addressed. The health impact assessment covers occupational and public health risks from routine operation and accidents. The book does not provide an in depth review of EIA methodologies, since these are described in specialised reports and guidebooks to which the reader is invited to refer (see Annex X, Bibliography).

The economic aspects addressed in the book cover direct costs (i.e. those internalised by electricity producers), and external costs (i.e. those borne by society as a whole, but not included in the cost of electricity) insofar as they can be valued. Beyond direct levelised costs of electricity generation, cost effectiveness assessment of mitigation options and measures, broad macro-economic impacts, and social costs and benefits of adequate electricity supply, technology development, and health and environmental protection are discussed. State-of-the-art methodologies for estimating and valuing externalities are described also.

The book highlights the main steps of a comprehensive approach to electricity system analysis for policy making purposes and indicates the types of methodologies, analytical models and computerised tools that can be used in support of decision making. However, it does not provide detailed descriptions of the different models mentioned. For in-depth information on computer tools for comparative assessment of electricity generation options and strategies, the reader is invited to refer to Annex I.

The book includes a short discussion of instruments and measures (such as taxes, subsidies, standards, regulations, research and development, and technology transfer) that decision makers might use in order to facilitate policy implementation and better achieve their goals and objectives.

The decision making process described emphasises the interactions between IAPs within an iterative dialogue aiming towards building a consensus on design and implementation of power sector policies. Beyond the techniques for assessing and valuing positive and negative impacts of alternative options and strategies, the process outlined in the book should allow decision makers to reflect perceptions of the problems and objectives that differ according to the interest groups and the countries or regions concerned.

1.4. Definitions of important terms

Some key terms are defined explicitly below because their meanings, as adopted for the purpose of this book, are essential for understanding the basic concepts underlying the integrated approach to policy making in the power sector, as described in the following chapters. The glossary (Annex IX) explains the meaning of additional important terms used in the book, for which it might be difficult to find commonly agreed definitions. Definitions of classic electricity system analysis and environmental impact assessment terminology can be found in specialised dictionaries and other published documents on energy, electricity and the environment.

Planning, in the context of the present book, means the overall process of analysing, assessing and comparing alternative strategies for electricity system expansion and operation. The objective of electricity system planning is to identify feasible paths, taking into account the technical, economic and environmental requirements and constraints chosen by policy making bodies. The results and outcomes from electricity system planning studies cover comprehensive and documented information on a series of possible alternative strategies, including the actions required for their implementation and their consequences. These results are intended for assisting decision makers in their choices and for informing IAPs on the implications of those choices.

Cost-benefit analysis is a method for examining and accounting for, insofar as feasible, the positive effects (benefits) and negative effects (costs) of undertaking an action. Cost-benefit analysis includes two main steps: identifying and quantifying positive and negative effects; and establishing an accounting framework for reporting all these effects with a common unit of measure, generally money. Identifying the effects of industrial activities in general, and of the electricity sector in particular, is relatively straightforward, although the impact inventory might remain incomplete owing to insufficient data and/or inadequate scientific knowledge. The major limitations of cost-benefit analysis result from the difficulty to establish a uniform accounting framework. Insofar as negative effects are recognised within the economic framework prevailing, their costs are internalised by producers and thereby automatically integrated in cost-benefit analysis. Externalities, i.e. positive and negative effects of industrial activities that do not affect producers and consumers directly, are not reflected by traditional market mechanisms and, therefore, are not integrated in classic cost-benefit analysis. However, new methodologies and tools are being developed for valuing externalities (see Chapter 4). For example, attempts are being made to assign monetary values to impacts of residual emissions, i.e. health and environmental effects of low level pollutant emissions, even when these are below the emission limits allowed by the regulations in force. With regard to health and environmental impacts of the power sector, external costs might be derived from physical impacts by using different approaches such as damage functions, costs of mitigation technologies or measures, and willingness of the affected parties to pay for avoiding a nuisance. Valuing and internalising external costs help to extend the concept of cost-benefit analysis.

Least cost planning (LCP) as applied in the power sector has the objective to schedule technically feasible electricity generation expansion paths in such a way that the total system costs, including investments, operating and maintenance and fuel, are minimised subject to certain constraints such as: meeting the projected power demand; adhering to technical specifications and operating conditions; and being feasible within the financial capability of the operator. LCP provides optimised solutions to resource planning problems taking into account direct costs that are borne by the producers and that are reflected by market mechanisms in the prices paid by the consumers. The LCP process, which has been the traditional approach adopted by utilities for system expansion planning, relies upon classic methods for minimising an economic objective function under constraints. In general, those costs that are not reflected by market mechanisms or regulations, such as social costs and health and environmental costs of residual emissions and burdens, are not captured by LCP and are not taken into account in the optimised expansion paths identified by this method. However, costs that are not reflected by market mechanisms can, in principle, be captured by LCP, provided that such ‘external costs’ are quantified and included in the objective function (see Section 4.7.3).

Integrated resource planning (IRP) subsumes least cost planning and incorporation of environmental impacts. IRP implies an interaction between the different actors - utilities, IPPs, governmental agencies, non-governmental organisations (NGOs), customers and IAPs. IRP places greater emphasis than LCP on demand-side management and energy conservation techniques and measures such as more efficient lighting devices and appliances, improved insulation of buildings and the development of technologies that consume less energy. IRP integrates policy guidelines that are designed to minimise the direct and external costs of the resources used at the electricity generation, delivery and end-use levels for supplying a given electricity service. Such guidelines may address: improvements of fuel quality (e.g. shifting to low sulphur content coal); network optimisation (e.g. interconnection of grids between neighbouring utilities or countries); decentralised (e.g. by renewable energy systems) versus centralised generation; and promotion of efficient end-use devices (e.g. through tax rebates and subsidies for facilitating market penetration of electric appliances with low specific consumption). IRP allows electricity producers to recover costs associated with reducing power demand and, therefore, avoiding the need for additional generation capacity, as well as investments in new generating capacities.

Enhanced electricity system analysis, as described in this book, incorporates classic IRP within a comprehensive assessment of the full energy supply system. Through integration of the electricity sector in the overall energy system, enhanced electricity system analysis broadens the scope of the analysis beyond the electricity producer view point, in order to minimise the overall resources used at the level of the country or region. Conceptually, enhanced electricity system analysis is not bounded by national borders and covers the costs and impacts of the entire energy system, independent of whether the costs and impacts occur inside or outside the country where the energy is consumed. Enhanced electricity system analysis extends the conventional cost-benefit analysis through an attempt to integrate the precautionary principle, which leads to reflecting in the policy making process the willingness to avoid an activity that likely would result in negative effects, even when the effects are not fully proven, assessed and assigned monetary values. For example, the precautionary principle calls for measures to mitigate greenhouse gas emissions, although the risks of global climate change remain scientifically uncertain.

It should be noted that the boundaries between the three approaches described above are rather flexible. An extended LCP approach may well include many features of IRP and even touch some areas of the enhanced analysis approach. Also, by making certain modifications during its application (e.g. using multi-scenario analysis to reflect the uncertainties in key factors; doing post-calculation analysis and comparative assessment of the alternatives), the IRP approach can encompass most of the additional features of the enhanced approach.

The main features of the three approaches are as follows:

- Least-Cost Planning (LCP):
    - Only supply-side options considered;
    - Exogenous demand projections, that are not modified by supply-side solutions;
    - Exogenous fuel price projections, that are not modified by fuel demands as derived from supply-side solutions;
    - Environmental issues considered as emission constraints; internalisation of external costs of supply-side solutions only in exceptional cases.
- Integrated Resource Planning (IRP):
    - Both demand-side and supply-side options considered;
    - Demand projections depend on energy price, as derived from supply-side solutions (i.e. price elasticity of energy demand accounted for);
    - Fuel prices depend on the amounts of fuel resources consumed, as derived from supply-side solutions;
    - Consideration of external costs is an integral part of the analysis.
- Enhanced Analysis:
    - Combines main features of LCP and IRP;

- Uses multi-criteria analysis for taking viewpoints of different IAPs into account;
- Treats uncertainties explicitly;
- Includes consideration of external costs for all stages of electricity generation chains (FENCH analysis).

One should understand also that the specific features of the enhanced approach, and even more so for the IRP approach, are not entirely new [see, for example, 2, 3 5, 6]. The need for comprehensive analysis was identified long ago, and some analysts included them into the analysis of electric power systems. However, it is only rather recently that these features became an unavoidable part of any serious electricity sector study.

1.5. Structure and contents of the book

This reference book is structured in five chapters and eleven annexes. This introduction and four main chapters present the overall framework and the different concepts that constitute the proposed enhanced electricity system analysis approach, and its application within the decision making process for the power sector. The annexes provide more detailed information on some specific topics and issues that are addressed only in a general way within the body of the book.

Chapter 2 presents the different elements of the analysis to be carried out in support of decision making for the power sector. First, it outlines the scope of the traditional approach of identifying technically feasible expansion plans that satisfy expected electricity requirements at the least cost. Next, it introduces the social, health and environmental aspects of the electricity sector and describes methodological and institutional frameworks for integrating these issues in the analysis of alternative strategies. Finally, it offers guidance on ways and means to reflect the view points and priorities of all the actors, i.e. producers, consumers, regulators and governments, in the design of energy mixes and strategies for electricity generation at the utility, local, national or multi-national (regional) level.

Chapter 3 deals with the overall process of planning in support of decision making. It describes a systematic, step by step approach that includes: identifying the problems to be solved; setting-up the goals and scope of the study; and presenting decision makers with alternative strategies designed to meet their objectives. The chapter covers: analytical framework; data collection, assessment and management; selection of relevant methodologies and tools; critical review and presentation of results usable by decision makers and IAPs; and eventually monitoring the results of implemented strategies.

Chapter 4 introduces the concept of the enhanced electricity system analysis approach proposed by this book, with the objective of supporting the design of sustainable strategies for the power sector. The chapter covers: demand side analysis and management; supply side analysis and management, including technology assessment and expansion planning approaches; impact assessment including some insight on processes for valuing and internalising external costs; and the concept of multi-criteria analysis, together with descriptions of some methods and tools for carrying out this type of analysis. Alternative means for integrating economic, social, health and environmental aspects in the evaluation process are presented.

Chapter 5 deals with evaluating the results from the analysis, the treatment of uncertainties, risks and social preferences, and establishing an effective dialogue between analysts, decision makers and IAPs. Some views are offered on implementation issues and ways and means to monitor the overall implications, i.e. macroeconomic, social and environmental effects, of the alternatives under consideration, as compared to the objectives defined by the decision maker.

Annex I provides a short description and background information on some state-of-the-art analytical models and computer tools currently used in decision support studies for the power sector. Emphasis is placed on the main characteristics, strengths and limitations of the tools presented, in order to help the reader in identifying analytical tools that might be relevant for specific purposes and objectives.

Annex II contains a brief description of the main energy sources and technologies for electricity generation.

Annex III highlights the potential environmental impacts associated with the principal energy chains and power plant technologies for electricity generation.

Annex IV addresses issues related to assessing and valuing external costs associated with environmental impacts from electricity generation systems, drawing from published literature on the subject matter. Results from recent scientific research projects and studies on external costs of energy chains for electricity generation are presented and discussed. Some key issues related to the application of external cost valuation and internalisation methodologies in decision making for the power sector are highlighted.

Annex V reviews issues related to the treatment of large accidents (e.g. severe nuclear accidents, oil tanker wrecks, dam ruptures) within the comparative assessment of electricity generation options and strategies. It focuses on risk assessment and impact evaluation, and the integration of effects from low probability/high consequence events, together with impacts from routine operation, into comparative assessments of energy chains.

Annex VI introduces the concept of Corporate Integrated Resource Planning (CIRP), through an example of its design and implementation. Although this example of CIRP was developed and implemented by a specific company, it illustrates the practical application of many of the ideas described in this book. The process of internalising externalities and involving the public in the decision making process, as illustrated in the example, represents an enhanced procedure that goes beyond the traditional utility oriented planning approach.

Annex VII presents a practical example of an actual Demand Side Management (DSM) programme. This example is intended to help in understanding the concepts of DSM and its implementation, as described in the main chapters of the book, by illustrating the application of DSM at the utility level and highlighting the main issues and difficulties encountered by the utility. Although the programme described in the example was implemented in an industrialised country, it is in principle applicable in developing countries also.

Annex VIII reviews a sample problem, based on a study carried out in Turkey, illustrating the step-by-step approach to decision analysis.

Annex IX (Glossary) gives definitions of some important terms, focusing on those related to concepts introduced and used in the book. It should be stressed that the glossary is not intended to be exhaustive in coverage, and that the definitions provided, although generally reflecting a consensus of views by experts in the field, strictly are applicable only within the context of the present book and might in some cases differ from definitions given in other published literature.

Annex X (Bibliography) offers a list of selected books, reports, conference papers and articles from scientific journals or trade publications, that elaborate further on some methodological and technical aspects dealt with in the book and that complement its content. The reader is invited to consult these documents for more information on many issues addressed only briefly in this reference book.

REFERENCES TO CHAPTER 1

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, The DECADES Project - Outline and General Overview, DECADES Project Document No. 1, Vienna (1995).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electrical Generating Systems: A Guidebook, Technical Reports Series No. 241, STI/DOC/10/241, Vienna (1984).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Health Impacts of Different Sources of Energy, Proc. of Int. Symp. (Nashville, 22-26 June 1981), IAEA Proceedings Series, STI/PUB/594, Vienna (1982).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Risks and Benefits of Energy Systems, (Proc. Int. Symp., Jülich, Germany, 9-13 April 1984), STI/PUB/668, Vienna (1984).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Format and Structure of a Database on Health and Environmental Impacts of Different Energy Systems for Electricity Generation, IAEA-TECDOC-645, Vienna (April 1992).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Methods for Comparative Risk Assessment of Different Energy Sources, IAEA-TECDOC-671, Vienna (October 1992).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY AND NUCLEAR ENERGY AGENCY (OECD), Nuclear Power: An Overview in the Context of Alleviating Greenhouse Gas Emissions, IAEA-TECDOC-793, Vienna (1995).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for Comparative Assessment of Health and Environmental Impacts of Electrical Energy Systems, Technical Reports Series No. xxx (in publication), Vienna (1998).

[9] WORLD BANK, Environmental Assessment Source Book, Technical Paper No. 140, Washington, D.C. (1991).

[10] MEIER, P. AND MUNASINGHE, M., Incorporating Environmental Concerns into Power Sector Decision Making: A Case Study of Sri Lanka, Environment Paper No. 6, World Bank, Washington, D.C. (1994).

[11] ADAMSON, S., BATES, R., LASLETT, R. AND POTOSCHNIG, A., Energy Use, Air Pollution and Environmental Policy in Krakow: Can Economic Incentives Really Help?, Technical Paper (Energy Series) No. 308, World Bank, Washington, D.C. (1996).

CHAPTER 2

ELEMENTS FOR CONSIDERATION IN ENHANCED ELECTRICITY SYSTEM ANALYSIS

2.1. General considerations

Electricity system analysis should be carried out while bearing in mind that the power sector: constitutes one part of the entire energy system; is linked with the overall economic system; provides social benefits; and has impacts on the environment.

Electricity as an energy vector has specific characteristics that make it attractive for many end-use purposes. It is easy to distribute, clean and efficient at the end-use point and has some non-substitutable uses (e.g. lighting, communications, computers, electric motors). Access to electricity services has proven to enhance economic development and social welfare. For example, electrification of rural areas in developing countries contributes to a better distribution of employment opportunities and a more equitable access to health and education services, as well as improving the overall standard of living.

For these reasons, the share of electricity in final energy has been increasing rapidly and this trend is expected to continue, in particular in developing countries. Worldwide, fuels for electricity generation represent about 36% of total energy demand today, and it is expected that at the end of the next three to four decades more than 50% of primary energy will be used for electricity generation.

Electricity consumption varies significantly between industrialised and developing countries. Industrialised countries represent less than 25% of the world population but consume more than 75% of the electricity generated world-wide. On average, electricity consumption per capita is around 500 kWh per year in developing countries, compared to more than 5,000 kWh on average in Europe (but much higher in Scandinavian countries) and more than 10,000 kWh in Canada and the USA [1].

At present, the electricity demand growth rate world-wide is over 3.6% per year, which is twice the population growth rate, slightly higher than the economic growth rate, and almost twice the primary energy demand growth rate. Although electricity consumption grew very rapidly in developing countries over the past three decades, with a 13-fold increase since 1960, consumption is still constrained by supply limitations (one third of the world population is still deprived of access to electricity), and the demand is expected to continue increasing dramatically. Even with strong efforts directed towards demand side management and reduction of the energy intensity of national economies, the World Energy Council (WEC) estimates that demand for electricity in the developing regions of the world will grow by a factor of 2-2.5 up to 2020 and by a factor of 4.5-6.5 up to 2050, relative to 1990 [2]. In OECD countries, on the other hand, electricity demand is estimated to increase only by a factor of 1.2-2 up to 2020 and to remain relatively flat from 2020 to 2050.

The analysis of statistical data and past trends does not allow generic relationships to be established between electricity demand, primary energy demand and economic growth. In particular, electricity demand growth depends not only on economic growth but also on the rate of substitution of electricity for other energy forms, including non-commercial energy sources. Nevertheless, given the outlook for population growth, increasing energy consumption per capita, and the growing share of electricity in total energy, world demand for electricity will continue to grow.

Most current technologies available for electricity generation, transmission and distribution are capital intensive. Therefore, large capital investments will be required in the power sector in order to cope with growing demand. For developing countries alone, the World Energy Council [2] estimated that the investment requirements will be some US $ 100 billion per year, in order to meet the projected electricity demand growth up to 2020. Additional investments will be needed in many countries for meeting environmental protection goals. For example, in regions where new regulations and/or standards will require controls on sulphur dioxide and nitrogen oxide emissions and where neither low-sulphur coal nor natural gas are available, the need to incorporate abatement devices will increase investment costs in the power sector by at least some 5 to 10%. This emphasises the importance of performing a comprehensive comparative assessment of different options in the design of economically optimised and environmentally benign strategies for the power sector. Specific issues related to mobilising the necessary financial resources are addressed in a recently published report by the World Energy Council [3].

Economic considerations led to the early development of methodologies and mathematical models designed for electricity system expansion planning purposes. The models implemented in the past were oriented primarily towards the achievement of business oriented goals, with emphasis being placed mainly on minimisation of cost, efficient allocation of financial resources and rational use of natural resources (materials and fuels).

Since, in many applications, substituting electricity for other energy forms increases the overall efficiency of energy use, electricity use tends to reduce health and environmental impacts from the energy sector. However, while electricity is an essentially clean energy form at the end-use point, its generation and transmission are potential causes of social, health and environmental burdens. Growing awareness of social, health and environmental issues has motivated the development of more comprehensive approaches to electricity system analysis and the implementation of enhanced models and evaluation techniques allowing the investigation of the relationships between the power system, the overall energy system, and the environmental and social context.

This chapter describes the evolution of the electric power sector planning process, shifting from traditional economic optimisation approaches towards approaches that are more comprehensive in the integration of economic, social, health and environmental aspects. Methodological and organisational frameworks for enhanced electricity system analysis are described. The chapter introduces some ways and means to deal with social, health and environmental issues, together with economic issues, within electricity system analysis aiming towards meeting electricity service requirements in a manner consistent with the objectives of sustainable development.

2.2. Traditional approach to planning

The traditional approach to electricity system planning, as used in the past, was driven by the primary objective of power sector development at that time, i.e. to meet the anticipated electricity demand at the minimum direct cost to the consumer. For this purpose, rather sophisticated generation capacity expansion optimisation models were developed and applied. One example of such planning tools is the WASP model [4], which is designed to minimise the total discounted cost of meeting electricity demands over some planning horizon (usually 20 to 30 years) and with a specified level of system reliability.

In the traditional approach, the aim of the planning process is to determine technically feasible power generation expansion alternatives, and their deployment schedules, that minimise the total system costs, while satisfying certain specified constraints. The main constraints imposed are that: the projected electricity demand be met within a specified margin of reliability; technical specifications and operating conditions be met; and the implementation schedule be technically and financially feasible. The planning activities undertaken within the traditional approach aim towards [5]:

- preparing a capital investment programme corresponding to the implementation of the required electricity generation facilities;
- developing guidance on government policies that could be used to influence the development of the electricity system, aiming towards achieving government objectives (e.g. reducing emissions of greenhouse gases);
- providing signals to the related industries and institutions regarding future orientations and trends in the power sector.

The preparation of capital investment programmes has been the main goal of electricity system expansion planning owing to the importance of financial and human resources committed by these programmes. The expansion plans were based upon detailed and reliable information on alternative options and systems, including: conversion efficiency of energy systems; reliability and performance of technologies; and capital and operating costs of facilities.

Generally, in the traditional approach to power sector planning, environmental considerations were not taken into account in a comprehensive way. Therefore, decisions on electricity generation technologies and energy mixes were based almost exclusively on comparative assessment of direct costs. However, environmental concerns were partly reflected through the costs of pollution controls required for meeting standards and regulations. Also, in the case of hydro power projects, easily quantifiable social costs (such as costs of resettlement and the opportunity costs of foregone production from inundated land) are now routinely incorporated into economic analyses.

Extensive examination of environmental issues usually were deferred to the environmental impact assessment (EIA) of specific projects. Impact quantification at this stage generally was carried out using mathematical models that simulated pathways of pollutants in the environment (e.g. atmospheric dispersion models for air pollutants, and thermal plume models for predicting ambient water temperature increases resulting from cooling water discharges). This type of EIA aims primarily towards checking compliance with prevailing standards and regulations, and investigating mitigation options to be implemented whenever required. An analysis of actual impacts, e.g. an estimation of the health risk associated with pollution exposure resulting from air emissions, rarely was part of such assessments.

Although there are increasing moves towards privatisation and deregulation of the electric power sector throughout the world , the traditional approach still is of some relevance. Most developing country utilities that are moving towards privatisation are doing so on a piecemeal basis. New plants may or may not be privately financed and owned. Approvals for these plants, however, still depend on utility and government review, and many such ‘privately financed’ plants rely on loan guarantees from international financial institutions. In some cases, financing for a new plant may be entirely private, but the sale of its electricity may be the subject of public agreement. If so, a comprehensive assessment of the entire system, with and without the proposed electricity sales agreement, could be used to determine a fair price for the electricity sold.

2.3. Social and economic context

The evolution towards a more comprehensive approach to electricity system planning emerged from a broader recognition of the need to investigate the broad social responsibility of the power sector.

The concept of social responsibility covers a number of issues ranging from local employment to rational exploitation of national resources. It implies a comprehensive analysis of natural resource requirements and social, health and environmental impacts arising at all steps of the energy chains constituting the electricity generation system.

The integration of the power system analysis and planning process within the social and economic context can be considered as a shift from ***minimising costs*** (i.e. direct costs of electricity production) to ***maximising effectiveness***. The concept of maximising effectiveness should be understood, in a broad sense, as an attempt to find solutions optimised from the view point of society as a whole. In this context, the planning process aims towards seeking preferred supply and demand side options and strategies for solving present problems in the power sector (e.g. supply shortages, high costs, non-compliance with environmental regulations), while addressing various objectives of the electricity utilities, the various actors in the energy and other economic sectors and, more generally, all IAPs.

This shift in emphasis entails a thorough revision of the overall objectives underlying the development of the power sector and of the parameters, data and assumptions that have to be considered in analysing electricity systems. In particular, the power sector has to be analysed as one part of the entire energy system within the overall economic and social context.

Within this more comprehensive framework, industrial activities are assessed taking into account, insofar as feasible, their total (direct and indirect) costs and benefits to society as a whole. In this perspective, decisions for the power sector should be based upon comprehensive cost effectiveness analysis and driven by the objective to maximise economic and social benefits (e.g. GDP per capita, security of supply, quality of life) through the choice of energy mixes minimising total economic and social costs. However, the decision makers often are driven by other short term objectives such as customer service, risk management, need for financial and technical flexibility, competitiveness, etc.

Difficulties in implementing this approach arise from present market imperfections (see the Glossary for definitions) and the existence of externalities whose costs are not reflected in the prices of products and commodities [6].

The power sector, like any other economic sector, has some social and environmental impacts that are not accounted for in the usual cost estimations. Environmental and natural resources are now recognised as being production factors similar to labour, capital and raw materials. However, current market mechanisms do not ensure efficient allocation of these resources for enhancing overall social welfare and do not take fully into account the need to conserve resources for the benefit of future generations. Owing to shortcomings in the identification and valuation of externalities, and inadequate integration of external costs in economic analysis, policies driven by current market forces might lead to depletion of natural resources and to environmental pollution levels exceeding those corresponding to optimal social benefit.

From the economic view point, market imperfections lead to unsatisfactory redistribution of revenues, resulting from inequalities in the relative prices of electricity and other energy carriers. Such inequalities may be in the form of subsidies, which prevent fair competition between energy service supply alternatives. It most commonly is expressed as a decreasing price-sales function. In order to reduce possibilities that a business risk may result from market imperfections, the utility's concern is focused on market mechanisms (e.g. advertising, pricing, product policy) for influencing its share in the overall energy supply market.

Owing to market imperfections, power sector planning cannot be carried out only at the project level nor be based only on the utility's economic objectives (e.g. maximising profits or minimising financial risks). The planning process should provide decision makers with relevant information allowing for a comprehensive assessment of the type and magnitude of market inefficiencies. Therefore, the analysis should cover all resources available on both the supply and demand side. Moreover, the decision making process, and the analysis that supports it, should be based upon well defined information and procedures that allow the building of adequate policies, irrespective of the instruments that might be used for their implementation.

For this purpose, a formalised method should be used not only to compare the merits of a set of actions, such as supply side investments or demand side management measures, but also to determine how to implement the chosen actions in the real world.

In order to create the conditions for improving the overall efficiency of power systems from a broad social view point, two types of activities should support decision making (see Figure 2.1):

- establishment of a **methodological framework** for identifying and assessing market imperfection indicators, and incorporating them in the decision making process;
- adaptation of the **organisational framework** in order to adjust power sector regulations aiming towards implementing the best measures for correcting market imperfections and limiting inefficient allocation of resources.

2.3.1. Methodological framework

As pointed out above, the comparative assessment of long term power system development alternatives should take into consideration the entire energy system and in particular the parts that are connected directly to the power sector. Accordingly, decisions in the power sector have to be taken in co-ordination with the overall energy policy and within the macroeconomic context of the country or region.

A multilevel hierarchical approach to complex energy system modelling presents a consistent way of dealing with links and interactions between the different elements and economic sectors that are related to the power sector. This approach offers a methodological framework for integrating electricity system planning in the optimisation of the overall energy system within the context of the national economy.

The hierarchical structure, e.g. the number of levels, depends on the scope of the analysis to be carried out. Figure 2.2 illustrates the concept of the hierarchical approach by showing a three-level structure that links the power sector to the overall energy system and the national economy.

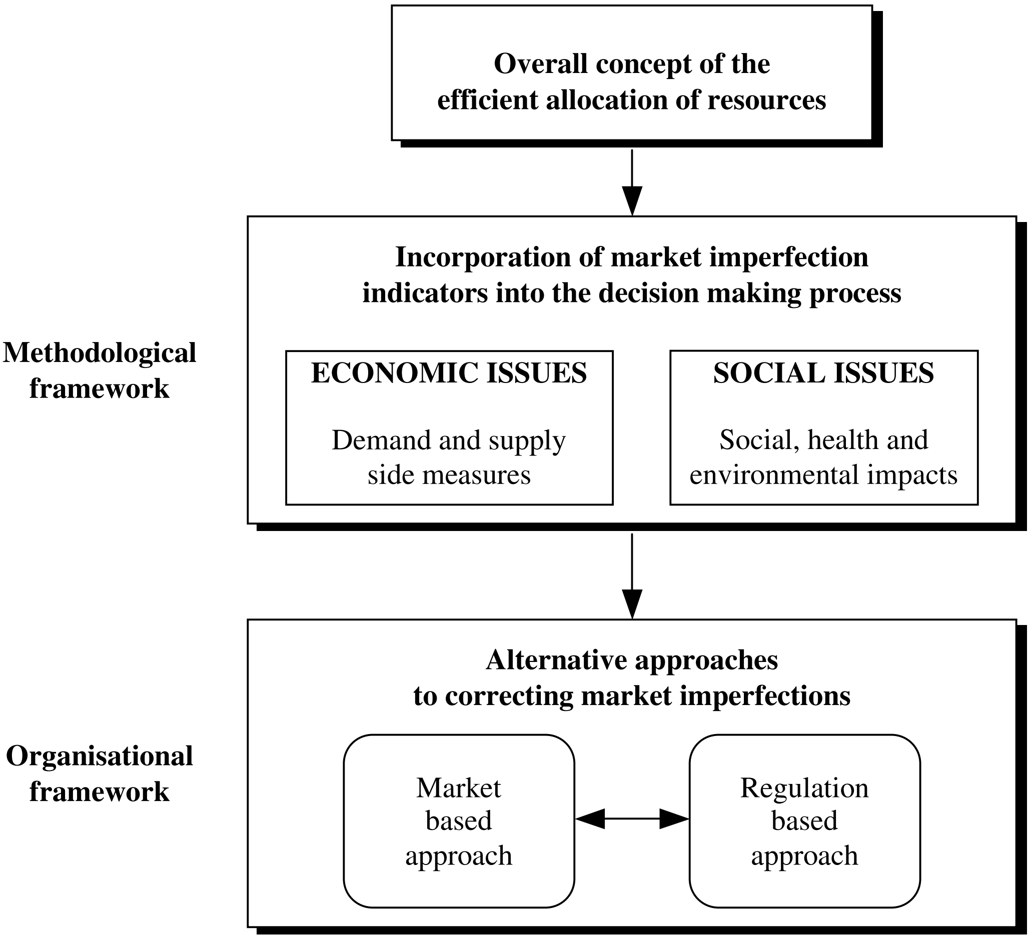


FIG. 2.1. Activities for effective allocation of resources.

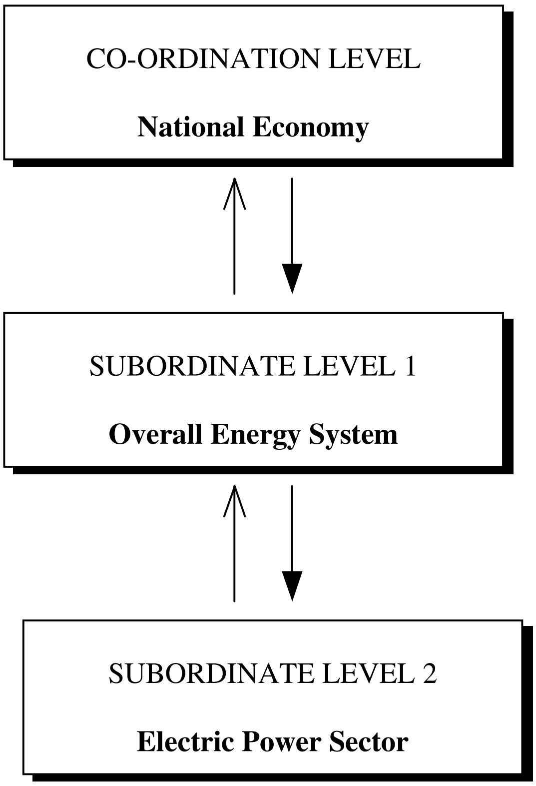


FIG. 2.2. Three-level hierarchical structure.

The analysis process is carried out using a family of interconnected models that reflect the position of the power system within the overall energy supply system and the national economy. The modelling approach starts at the co-ordination level and each subordinate level is co-ordinated with the one above. At each level, co-ordination information is received from the higher levels, and information generated is transmitted back, up to the co-ordination level. Each level determines some basic parameters of co-ordination:

- the co-ordination level determines the estimated requirements for final energy supply and its structure, based upon expectations and goals for the development of the national economy;
- the energy system level determines the optimal energy flow and the end-use fuel mix;
- the power sector level determines the market share of each electricity generation option as well its corresponding primary energy consumption.

2.3.2. Organisational framework

The frameworks governing economic activities, and striving to achieve an efficient allocation and use of resources, generally are implemented by governments at the national level. These frameworks include laws and regulations (e.g. environmental regulations and emission standards), energy tariffs and taxes, and a number of other measures aiming towards making the economy beneficial for the society as a whole. The overall objective of economic regulation is to harmonise conflicting goals such as social acceptance, economic competitiveness and equity between present and future generations.

The power system has some special features that have to be taken into account when designing organisational frameworks for its regulation:

- electricity transmission and distribution through a network creates a situation of technical monopoly;
- owing to the fact that electricity is essentially a non-storable commodity, an exact balance between supply and demand has to be achieved at all times;
- the power sector traditionally has been characterised by long lead times for implementing new projects and long life times of the facilities; however technological development is resulting in options with shorter lead times;
- in some countries, electricity supply is considered to be a public service activity while in other countries it is treated more or less as any other market product or commodity;
- although enhanced analysis will play a different role in a competitive market economy than in a centralised structure, such analysis procedures still will be useful.

Government intervention in the power sector is motivated by the need to correct market imperfections and by the government's desire to satisfy its policy objectives. Many different organisational and regulatory frameworks have been implemented to achieve efficiency and to provide social effectiveness. Organisational frameworks may be vertically integrated or unbundled, and regulatory frameworks may establish a monopoly or allow for free market competition. These frameworks differ according to the approach (regulation or market oriented) adopted by governments to correct market imperfections.

The organisational framework defines relations between the economic agents that constitute the energy/electricity market. Three different types of organisational frameworks [Ref. 6] prevail in the power sector, each of them characterised by different emphasis being put on regulation and market mechanisms for co-ordinating the sector:

- vertically integrated system;
- unbundled structure;
- competitive electricity market.

In a **vertically integrated system,** one company manages the power system and is responsible for electricity generation, transmission and distribution activities. In this structure, the monopolistic position of the company calls for application of governmental control in order to prevent adverse consequences from the lack of competition. In particular, measures can be taken at the co-ordinating level to oblige the company to undertake activities which are not necessarily associated with earning profit, but may be considered desirable in order to meet social objectives.

In **unbundled structures**, electricity generation activities are separated from distribution. However, generation on one side and distribution on the other side may remain integrated in a similar way as in the vertically integrated structure. In that case, there is no competition at the level (generation and/or distribution) that is integrated. Therefore, organisation frameworks may differ according to the level of competition prevailing on the supply side. The unbundled organisational framework is characterised by:

- the form of an unbundled system;
- the extent of regulatory based versus market based co-ordination.

When generation companies are independent, they have the opportunity to transport electricity through the transmission system and through the regional distribution network. Thereby, competition to supply wholesale customers, namely to supply companies and large industrial consumers, is established.

Competition imposes modification of the electricity system planning and decision making process. Decisions are taken at the level of each utility and driven mainly by market forces; energy mix choices generally are not based upon the overall system optimisation but the analysts are looking for plans or strategies that are robust in addressing economic, environmental and social objectives in the face of future uncertainties. Decision criteria are different than in the vertically integrated structure and the planning horizon usually is shorter. Utilities tend to prefer investment alternatives which would provide low business risk and high operational flexibility, i.e. low share of investment in total electricity generation costs and high share of variable costs in total operating costs. Such an organisational structure may limit energy conservation measures to distribution companies which are in a monopolistic situation.

In a **competitive electricity market**, the organisational framework corresponds to full competition of all actors at all levels of the power system. Electricity producers compete with each other in their sales to distribution utilities and in some cases to end-users. Independent sales companies and electricity brokers have access to the market. The electricity prices are set in the market place.

In this context, decisions are driven essentially by market forces, i.e. each competing company tends to maximise its profit by: meeting customer needs; increasing its market share by improving its ability to meet competition; and decreasing its business risk by increasing the flexibility of its investments. Long term optimisation models may have only limited relevance for decision support studies in this type of market, since decisions usually are based on short term objectives.

In a competitive electricity market context, regulation is less direct since, in principle, governmental interventions should not interfere with market forces. Market oriented policy instruments are available to decision makers at the government level for enabling effective trade-offs between meeting electricity demand at affordable costs and protecting the environment [7]. Tools that may be used, such as prices, taxes, national tradable permits, development and transfer of ‘clean’ technologies and R&D orientation, are interdependent. These policy instruments should make use of market forces in order to be effective and to ensure sustainable economic development.

The aim of an energy policy is to provide secure, diverse and sustainable supplies of energy in forms that people and businesses want, and at competitive prices. It can be achieved best within a framework of regulations to protect health, safety and the environment. This view is coupled with recognition of the challenges presented by the need to move towards more environmentally sustainable development, and implies that some way must be found for the market to recognise and respond to the full value of the environmental impacts (externalities) of different technologies.

The market cannot give proper weight to environmental considerations unless the costs of environmental damage or the benefits of environmental improvement are built into the prices charged for goods and services. This effectively is a call for ‘full cost pricing’ of energy, and also of other products, which takes the familiar notion of ‘the polluter pays’ a stage further. Conventional indicators of economic growth do not take into account the impacts on the environment and the loss of some natural resources that are caused by that growth; therefore, they fail to measure the real increase in ‘standard of living’. Many experts are of the opinion that further research needs to be carried out in order to develop better indicators of real economic growth.

Relations among the actors may vary from system to system depending on the organisational framework. For the integrated type of organisation, the role of the regulatory authorities often is assumed to be essential in order to influence the power system behaviour in a direct way, aiming towards complying not only with the general policy but also with other social objectives. Such a centralised planning process offers opportunities for its extension toward the concept of enhanced electricity system analysis at the utility level.

In the competitive business environment, the market is allowed to dictate development of the power system, through economic choices. This type of organisation imposes separation of a utility’s motives from general objectives of the overall society. Thus, the role of the regulatory authorities becomes more complex and their actions less direct. They have to design general rules preserving the benefits of increased competition, taking into account the social health and environmental consequences of power system operation and development. In order to co-ordinate existing market imperfections consistently, enhanced electricity system analysis should be organised and implemented at the national level. As an analytical framework, it should participate in the harmonisation of the power system development and its social, health and environmental impacts.

2.3.3. Electric utility regulation in market economies

In industrialised market economy countries, especially in the USA, utility regulation has been practised for many years, and there are numerous books and reports on the subject. Some basic concepts in electric utility regulation that are important from the general planning point of view are [8]:

1. Protection of the utility's right to dispatch its generating units on the basis of short-run marginal cost;
2. Provisions for automatic pass-through, in electric rates charged to consumers, of increases and decreases in the cost of fuel and the cost of imported electricity;
3. Establishment of price controls that have the effect of constraining the rate of return on equity to be close to a 'target' value selected by the regulatory commission;
4. Requirement for 'least cost planning' of new generation, transmission, and distribution facilities so that the cost of electricity is minimised over a time frame of 20 years or more, while the reliability and quality of service is maintained at a certain specified level;
5. Provisions for competitive bidding among non-utility companies for the right to build and operate generation or cogeneration facilities that sell power to electric utilities under long-term contracts.

2.4. Environmental, health and social impacts

It now is recognised that addressing environmental, health and social issues is essential in electricity system analysis for decision making purpose. A large number of environmental, health and social impacts may arise from electricity systems (see Annex III and Chapter 4). Table 2.1 provides a non-exhaustive list of the types of impacts resulting from power system activities, which shows that these impacts are interdependent (e.g. soil changes and decreased nutrition, land disturbance and population resettlement). This means that attention should be given to avoid double counting when assessing the overall impacts of an electricity generation chain or system.

TABLE 2.1 TYPES OF ENVIRONMENTAL, HEALTH AND SOCIAL IMPACTS ARISING FROM ACTIVITIES IN THE POWER SECTOR

ENVIRONMENTAL IMPACTS	HEALTH IMPACTS	SOCIAL IMPACTS
Water contamination Land disturbance Ecosystem destruction Land pollution Marine and coastal pollution Air pollution Damage to buildings and monuments Soil changes Forest and crop degradation Climate change	Public disease Occupational disease Public accidents Occupational accidents	Income distribution Unemployment Urban migration Emigration Population resettlement Nutrition decrease

The type and importance of the various impacts resulting from electricity system operation vary widely, and their significance in a given analysis and planning exercise depends on the scope and objectives of the exercise. Therefore, it is necessary to identify and select, within a given study and context, key impacts to be considered in the assessment of alternative options for electricity supply and demand side management. The selection should reflect the significance of the impacts from the local, national, transboundary and global view points, taking into account the focus and limits of the analysis, and the objective of the planning exercise (see Chapter 3). The selection of key impacts implies some trade-offs between comprehensiveness and feasibility of the analysis.

The analysis of environmental, health and social impacts of the power sector should endeavour to be comprehensive in scope, i.e. to include all the steps of energy chains constituting the electricity system, from primary energy source extraction through transportation and conversion, to waste disposal. It also should be, insofar as feasible, comprehensive in coverage of effects; i.e. the analysis should proceed systematically from the source of emissions, through dispersion and exposure, to impact assessment.

The impact pathway methodology (See section 4.5.2.) provides a systematic framework for evaluating impacts from emissions and other residuals arising from industrial facilities. This methodology covers the main steps described below [9]:

Source term: characterisation of technologies by an ‘emission coefficient’ expressed in quantity of pollutant per unit of output from a given facility (e.g. tonnes of SO_2 per kWh);

Dispersion: calculation, using more or less sophisticated dispersion models, of the pollution concentration increment in affected regions, expressed in units of increase in ambient concentrations for a given area (e.g. added grams of SO_2 per cubic metre of air in the region affected by the operation of the facility);

Impact: calculation of physical impacts corresponding to increased exposure of humans, animals and ecosystems to pollutants, using dose-effect relationships (e.g. reduction of crop yields resulting from the deposition of SO_2); for full assessment of impacts, it is necessary to specify the distribution of receptors that are sensitive to the evaluated impacts (e.g. location of population, buildings, agricultural crops, forests, lakes, etc., affected by sulphur dioxide or acid rain);

Valuation: estimation of the monetary value of the impacts (e.g. reduction of revenues in the agriculture sector due to SO_2 effects). The last part of the valuation is the determination of the fraction of the damages that has not been internalised already (e.g. by government regulations). This fraction is the ‘external cost’.

Provided that all key impacts could be assessed and valued, the outcome from an impact pathway analysis would provide a total cost figure characterising the overall social, health and environmental impacts of the electricity system considered. In real life, however, the analysis can seldom, if ever, be exhaustive. Moreover, even when physical impacts can be evaluated fairly well, it might be difficult to associate relevant cost figures to impacts such as illnesses, loss of human life or visual intrusion (see Chapter 4). Therefore, simpler impact estimation approaches are often used in decision support studies, and decision makers have to rely on multi-criteria techniques for comparative assessment of the overall impacts of alternative options (see Chapter 4).

The World Bank study on power system planning in Sri Lanka [10] illustrates the use of simplified approaches for impact assessment. In that study, health impacts were estimated by the population-weighted increment in the air concentrations of particulates, sulphur dioxide and nitrogen oxides that would result from the operation of a power plant. Also, emissions of sulphur dioxide and nitrogen oxides were used as proxies for the effects of acid rain, rather than evaluating these effects explicitly. Such approaches can provide reasonably reliable estimations of the impacts in many cases when more comprehensive methodologies cannot be used owing to lack of data and/or time and manpower to run sophisticated models and tools.

2.5. Towards sustainable development

The concept of sustainable development, introduced in the 1980s [11], gained momentum through the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro (Brazil) in 1992. Agenda 21 [12], adopted by UNCED, called for development strategies aiming towards environmental protection and inter-generation equity, and emphasised that environmental and development concerns should be integrated into the process of decision making. The Second Assessment Report (SAR) of the Intergovernmental Panel on Climate Change (IPCC) emphasises that mitigation options for alleviating the risks of global climate change should be assessed comprehensively and adequate policies be implemented to promote the installation of the most environmentally benign energy conversion technologies. The Kyoto Conference in December 1997 adopted a Protocol to the Climate Change Convention aiming towards lowering overall emissions of greenhouse gases. The Protocol will entail industrialised countries reducing their collective emissions of greenhouse gases by 5.2% in the time frame 2008-2012, relative to levels in 1990.

Sustainable development *does not mean* having less economic growth. On the contrary, a healthy economy is better able to generate the resources for environmental improvement and protection. It also does not mean that every aspect of the present environment should be preserved at all cost. What it requires is that decisions throughout society are taken with proper regard to their environmental impact.

Sustainable development *does mean* taking responsibility for policies and actions. Decisions by utility managers, the government or the public must be based on the best possible scientific information and analysis of risk. When there is uncertainty and the consequences of a decision potentially are serious, precautionary decisions are desirable. Particular care must be taken where effects may be irreversible. Cost implications should be communicated clearly to the people responsible and the proper tools of analysis have to be applied in support of policy making.

Diversity in energy supply also has a role to play in reducing environmental costs. From the environmental point of view, diversity can spread environmental impacts between types of pollutants and across different regions, thus minimising the risk of an overload of one pollutant in one area.

It increasingly is acknowledged that human well being is not the sole criterion for protection, but that humans have a responsibility for protecting other forms of life also. These issues would be more evident to policy makers and the public if the external cost associated with different fuels or technologies were internalised in the price paid by the electricity consumer.

The concept of sustainable development therefore implies new rules and procedures in the process of electric system planning. Economic, social, health and environmental considerations will have to be integrated into the decision making process. The full implications of long term electricity supply strategies have to be considered, as opposed to project by project decisions. What previously was a process carried out by the management of the electric utility, with the concurrence or tacit approval of the regulatory authorities, now has become an iterative process involving different actors (public, utility, regulators and financial market). The process of enhanced electricity system analysis can be understood therefore as an integrated part of a collaborative process that involves all IAPs.

In the power sector, this new concept calls for incorporating three fundamental principles in energy/electricity/environment analysis:

- economic efficiency;
- sustainability;
- precaution.

Accordingly, the analysis should endeavour to combine these three principles, or make trade-offs between them, in order to identify development paths that are acceptable socially.

Placing stronger emphasis on sustainability and precaution implies an increasing role for economic and policy measures, regulations and standards, aiming towards alleviating and/or mitigating the impacts that might affect both present and future generations. Policies implemented so far in industrialised countries for enhancing sustainability rely mainly on regulation.

Sustainable policies for the power sector have the objective to: achieve adequate, secure and diverse supply at low total cost; and protect human health and the environment. Recognising that free market forces may not achieve sustainability, the efficiency of policy interventions that may help sustainability should be explored [13]. Development patterns that are more sustainable can be promoted by regulations imposing limits on environmental emissions and other burdens. However, having recognised the economic and social value of sustainable development, the way forward should be to set up a framework allowing market mechanisms to reflect the full environmental, health and social costs of alternative technologies. This calls for 'full cost pricing' of electricity, going beyond the 'Polluter Pays Principle' adopted by the Council of the OECD in 1974, based upon the development of economic indicators reflecting the value of natural resources, the environment and the welfare of future generations.

It should be pointed out that the concept of sustainable development does cover *development* as well as *sustainability*. Development, in the sense of economic growth, does contribute to enhancing social welfare and environmental protection, provided that adequate allocation of resources for this purpose is ensured. Also, environmental protection measures should be evaluated on the basis of comprehensive cost/benefit analysis, i.e. taking into account their full costs as well as benefits to society as a whole.

Diversity of supply has a role to play in sustainable energy/electricity strategies. From the environmental protection view point, diversity of type and origin of energy sources in electricity generation allows to reduce the risks of excessive emissions of one pollutant and/or excessive concentration of impacts in one area. Also, diversity of supply reduces the risk that exclusive reliance be placed on one energy source, that might prove in the future to have unexpected and unacceptable health or environmental effects.

The wide range of uncertainties prevailing in assessing the impacts from different energy chains makes it difficult to design and implement sustainable strategies in the power sector. It is agreed generally that environmental impacts from the power sector should be reduced and that, in case of uncertainty, the precautionary principle should be applied. However, uncertainties on damage functions, i.e. relationship between pollutant concentration and effects, raise some concerns and difficulties. With present scientific knowledge, it is not possible to demonstrate that there are not sharp discontinuities in dose/effect relationships. For example, there is only limited knowledge of the ecosystem impacts that may be associated with global climate change, but many scientists are concerned about possible abrupt collapse of ecosystems in case of global warming. The application of the precautionary principle in this context of uncertain, but possibly large and irreversible, impacts calls for the implementation of mitigation measures, the cost of which can be interpreted as an insurance premium against uncertain but potentially catastrophic effects.

The implementation of sustainable development requires responsible behaviour. Decision makers, IAPs and analysts should endeavour to base their assessments on the best information available regarding economic, environmental and social aspects of existing electricity systems and alternative options for their development. In case of uncertainty, in particular when the consequences of a decision might be serious and irreversible, the precautionary principle should be applied, with due consideration of cost implications. Adequate tools should be used to analyse, insofar as feasible, the impacts and risks associated with a decision, and the results should be brought to the attention of those responsible for and affected by the decisions that will be made.

The concept of sustainable development implies a revised approach to electricity system analysis in support of decision making. Economic, social, health and environmental considerations will have to be integrated into the decision making process. The totality of the future system plan has to be considered, as opposed to project by project decisions. The decision making process should involve not only electricity utilities and regulators but also all IAPs. Environmental protection criteria, in a broad sense, should acknowledge impacts not only on human being but also on other forms of life and on ecosystems.

A number of methodologies and tools are available for enhanced electricity system analysis (see Chapter 4), including methods for estimating external costs of alternative options (see Chapter 4) and for internalising those costs [Ref. 9] and reflecting them in the price paid by consumers. For example, the integrated pollution control approach [14] acknowledges that a balance is needed among potential polluters and the various areas at risk.

REFERENCES TO CHAPTER 2

[1] UNITED NATIONS STATISTICAL DIVISION, Energy Statistics Data Base (1993), UN, New York (1995).

[2] WORLD ENERGY COUNCIL AND INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, Global Energy Perspectives to 2050 and Beyond, World Energy Council, London (1995).

[3] WORLD ENERGY COUNCIL, Financing the Global Energy Sector - The Task Ahead, World Energy Council, London (1997).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Wien Automatic System Planning (WASP) Package: A Computer Code for Power Generation System Planning - Version WASP-III-Plus User's Manual, Computer Manual Series No. 8, Vienna (1995).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electrical Generating Systems: A Guidebook, Technical Report Series No. 241, STI/DOC/10/241, Vienna (1984).

[6] UNION INTERNATIONAL DES PRODUCTEURS ET DISTRIBUTEURS D'ENERGIE ELECTRIQUE, Integrated Resource Planning and Demand Side Management in Europe: Present Status and Potential Role, TAROPT/Rep. 06004Ren9428, Paris (1994).

[7] TURK, V. AND PANGERC-PAHERNIK, Z., The Slovenian Approach to the Integrated Planning, CIGRE Study Committee 37 (Power System Planning and Development), Report No. 37-93 (SL) 02 (E) (5 October 1993).

[8] ZIMMERMANN, C.F., Electric Utility Regulation in a Market Economy, Presentation in Seminar on Energy Supply in Budapest, Hungary, May 22, 1991: RCG/Hagler, Bailly, Inc., Washington, D.C. (1991).

[9] EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 1, Summary, Report No. EUR 16520 EN, EC/DG-XII, Luxembourg (1995).

[10] MEIER, P. AND MUNASINGHE, M., Incorporating Environmental Concerns into Power Sector Decision Making: A Case Study of Sri Lanka, Environment Paper Number 6, World Bank, Washington, D.C. (1994).

[11] WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT (Brundtland, G.H., Ch.), Our Common Future, Oxford University Press, Oxford, England (1987).

[12] UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT, Agenda 21 - Action Plan for the Next Century, United Nations, New York (1992).

[13] PEZZEY, J., Sustainable Development Concepts - An Economic Analysis, Environment Paper Number 2, World Bank, Washington, D.C. (1992).

[14] "This Common Inheritance, Britain's Environment Strategy", HMSO, London (1990).

CHAPTER 3

THE PROCESS OF ENHANCED ELECTRICITY SYSTEM ANALYSIS

3.1. Introduction

The ultimate objective of the enhanced electricity system analysis approach presented in this book is to support decision making by providing reliable, documented information upon which robust decisions can be taken. The analysis carried out with this objective in mind should aim towards identifying explicit solutions (e.g. electricity system expansion plans and demand side management measures) to specific problems formulated by decision makers (e.g. meeting a given demand growth at the lowest direct cost while satisfying environmental protection standards and regulations prevailing in the country).

This chapter gives an overview of the overall framework and consecutive steps of a planning procedure that supports decision making in the power sector. The systematic approach described in this chapter defines the consecutive steps in the interaction between the decision maker and the planner to: clarify the task; carry out the analysis; and interpret the results. The chapter is designed as a pragmatic step by step guide, leading the reader through the procedure and describing how it is integrated into the decision making process.

In recent years, the traditional utility oriented decision making process has changed to involve a larger number of actors. Figure 3.1 shows a schematic diagram of the respective roles and responsibilities of the three main groups of actors involved in the decision making process. ***Decision makers*** have the key responsibility for identifying the problems needing solution and for choosing from among the possible solutions derived by decision support studies, according to their own values and priorities, as well as the political and social context. ***Interested and affected parties (IAPs)*** have an important role to play in the decision making process, and their view points and concerns have to be recognised and taken into account insofar as feasible at each step. The role of energy/electricity ***analysts*** is to formulate the decision maker's problems in an analytical framework and to derive alternative possible solutions, taking into account relevant constraints (e.g. emission limits) imposed by regulators and the concerns (e.g. preservation of scenic areas) expressed by IAPs.

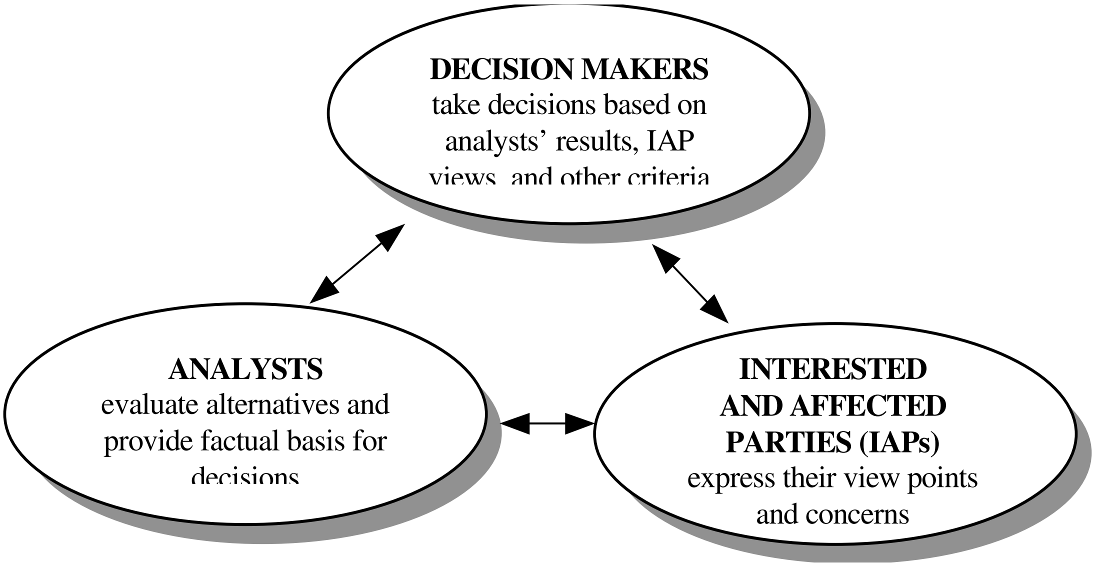


FIG. 3.1. Schematic diagram of interactions in the decision making process.

The decision making process in the power sector may be characterised by: complexity; a wide range of uncertainties; the large economic and environmental consequences at stake; and the lack of complete market freedom (i.e. the sector is constrained by regulations and controls). Because of these characteristics, the process should rely on a thorough, comprehensive and integrated analysis. The analysis framework should endeavour to consider all actors, all economic sectors, all available energy sources, transboundary and international aspects, and social, health and environmental impacts. Also, recognising the uncertainties prevailing with regard to future development in the power sector and the broad economic and environmental impacts of any decision taken for the sector, it is particularly important to aim towards robust solutions, i.e. paths that remain near the optimum under various circumstances and especially when parameters that cannot be controlled by the decision makers (e.g. prices of primary energy sources on international markets) may change significantly over time.

The electricity sector is characterised by: on the supply side, multiple producers, technologies and facilities; and on the demand side, multiple users each with multiple electricity service requirements. The explicit and implicit links between the power sector, other economic sectors, international markets and the natural environment are complex. In such a context, decision support studies require a series of detailed investigations covering future demand analysis, alternative supply option evaluation, and economic, social and environmental impact assessment. Each of these aspects deserves in depth analysis. For example, supply options should be evaluated on the grounds of a number of different criteria, including natural resource availability, technical and industrial development, economic competitiveness, environmental impacts and social acceptance. Analytical models, data bases and other computer tools can help the analyst in dealing with these inter-linked issues. However, the results provided by computer tools need critical review by a multi-disciplinary planning team with relevant expertise in the different aspects of electricity system analysis. Detailed results on various aspects, obtained in most cases by using different methodologies, should be carefully evaluated, compared and combined in a coherent manner in order to come up with consistent results and conclusions that could provide information that is useful to decision makers.

The decision making process has to take into account view points and priorities that often are conflicting, and should aim towards maximising, insofar as feasible, the satisfaction and welfare of all IAPs. In the power sector, IAPs include a wide range of actors such as utility shareholders, consumers, tax payers, population affected by and benefiting from a power plant project or demand side management measures. The increasing awareness of the public on social and environmental issues, and the concerns expressed by interest groups, non-governmental organisations (NGOs) and local communities, are leading to more involvement of IAPs at each stage of the decision making process. Initiating the dialogue with IAPs as early as possible in the process, in particular while identifying the problems to be addressed and defining the objectives of the decisions to be taken, makes it easier to obtain their understanding of the issues at stake and their acceptance of some trade-offs, e.g. higher electricity prices in exchange for avoiding or reducing environmental impacts. Due to the continually changing institutional framework, the decision making process has to undergo continuous evolution and adaptation. However, while the planning process and its interaction with decision making process is described in this Reference Book, the institutional framework is only touched upon briefly.

The process of analysis, planning and decision making for the power sector should be regarded as dynamic, since changes occur constantly regarding the electricity system itself and the context in which it is operated. The process should be repeated whenever necessary to reflect significant changes that have occurred in the assumptions, parameters and criteria adopted previously. Some exogenous assumptions and parameters, such as prices of imported fuels, cannot be predicted nor controlled by the planning team or the decision makers. Their evolution might necessitate revisions and modifications to previous plans. The process should be iterated also whenever: regulations have been modified (e.g. new atmospheric emission limits have been adopted in the country or region); new problems have emerged (e.g. health impacts of some polluting emissions have been reassessed); or new criteria have been introduced in the evaluation of alternative strategies (e.g. risk of global climate change or preservation of biodiversity). It is also desirable to update and revise decision support studies whenever input data availability and quality have improved.

The operation of the electricity system is complex and interlinked with other sectors. Changes in one part of the system can cause undesired and unanticipated changes in other parts of the system. The main goal of decision makers is to improve the overall performance of the whole system, to increase the efficiency, reliability and safety, to decrease the impacts and costs, and to satisfy the preferences of IAPs. The impacts and effectiveness of decisions can be anticipated only through using the system analytical approach. The effects of application of different measures for improving the performance of electricity systems have to be carefully analysed before implementation.

The planning process, from the decision maker's first identification of a problem, to a planning request to the analysts, culminating in a detailed system analysis, is quite time consuming and requires a series of comprehensive actions from the planner. The terms which are used by the decision makers are different from the language of system analysts. The planner has to be able to: understand the problems posed by the decision maker; transform these problems into the terms that are relevant for the different models; carry out the system analysis; and finally, present the results of the analysis in the decision maker's terms. The series of steps which have to be carried out in the interaction between the decision making and the planning process, can be interpreted in different ways. The structured analysis procedure is one example of methodological approaches developed for electricity system analysis and decision support studies (see Figure 3.2).

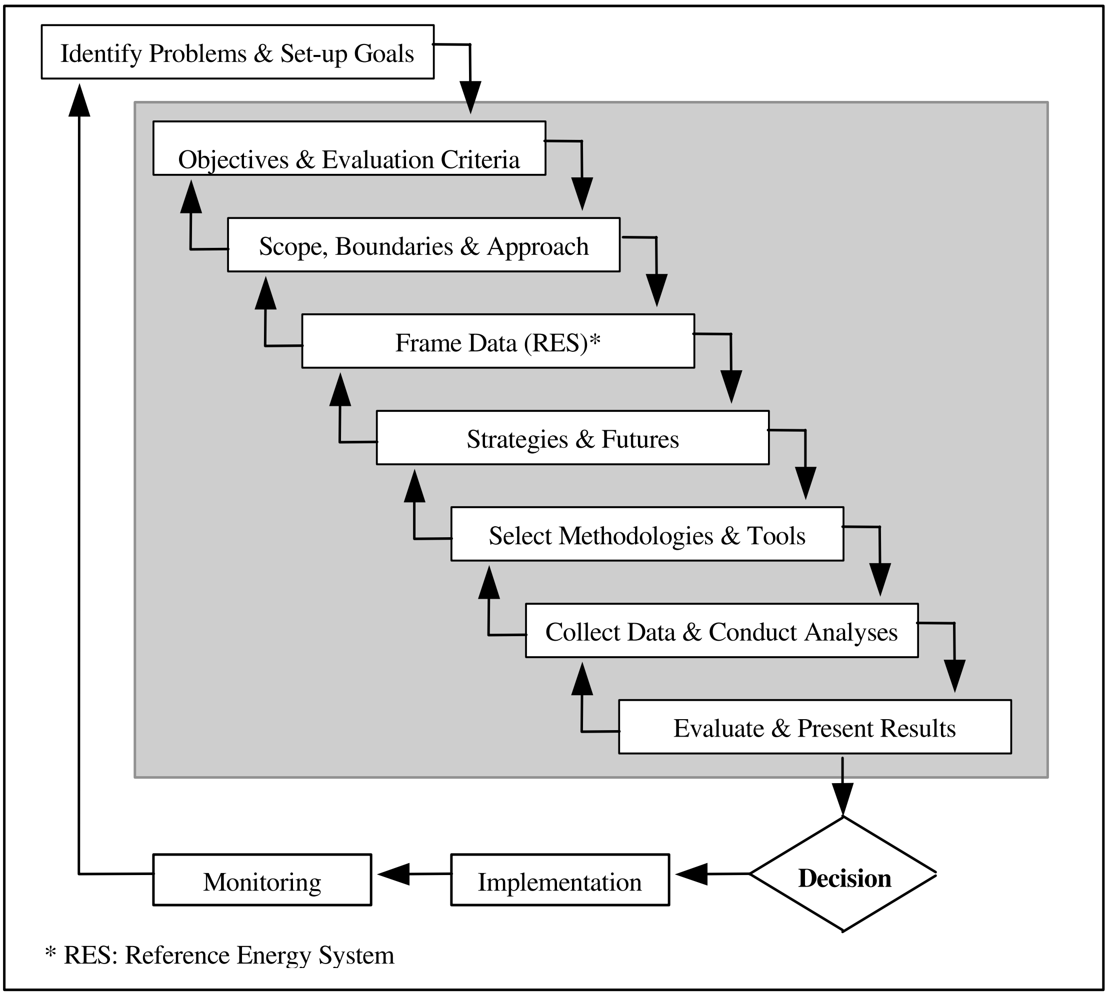


FIG. 3.2. Structured procedure for enhanced electricity system analysis in support of decision making.

The step by step approach provides a coherent and pragmatic framework for: managing data; selecting and using appropriate methodologies and tools; handling uncertainties; and dealing with multiple criteria and objectives. It allows to bring together hypotheses and assumptions in a consistent case study which provides decision makers with relevant and reliable results and conclusions. The following sections describe the scope and objectives of the successive steps.

For the successful accomplishment of a planning process, the planners have to understand that the translation of a task defined by a decision maker requires the understanding of technical problems and also the interpretation of the preferences of the decision maker. The objectives of planning are determined not only by the technical nature of the problems to be solved, but also by the preferences of the decision maker. Before covering the steps illustrated in Figure 3.2, the next section discusses some general problems in connection with the formulation of the planning task.

3.2. The decision maker's preferences and the formulation of the planning problem

3.2.1. Planning under uncertainty

When the uncertainty surrounding a particular decision problem has been formalised within a probabilistic framework, the decision maker's subjective attitude towards risk (i.e. of choosing a sub-optimal solution) can be described by a 'utility function'. This utility function reflects the trade-offs that the decision maker is willing to make between different outcomes (associated with the different choices) and their respective uncertainties. Different decision makers will have different attitudes towards risk, and these can be reflected in their individual utility functions. Utility functions are not always easy to derive, but their use has the advantage of providing a formal and clear formulation of the decision problem.

Consequently, one of the lessons that can be obtained from this formulation of the problem is that the correct decision criterion would always be determined by the attitudes and beliefs of each decision maker. Therefore, it can be concluded that there is no 'universal solution' to the capacity expansion problem (or to any other decision problem), because the 'best' solution will differ from one decision maker to another and will depend on their particular acceptance of, or aversion to, risks and uncertainties.

3.2.2. Multi-objective decision problems

Another aspect which becomes enlightened by the problem formulation described above is related to the multi-objective nature of the problem. Because the different objectives of the problem tend to be mutually exclusive, the selection of the 'best' option requires the formulation of trade-offs among the different attributes used to evaluate the performance of the several possible system designs. Such trade-offs require a multi-objective analysis in order to assess and compare the relative merits of the different options. In practice, a multi-objective analysis usually does not yield a single optimal plan. Therefore, the choice of the 'best' solution, from among possible solutions identified by the analysis, requires that the decision maker's preferences and value trade-offs among conflicting objectives be clearly articulated and made explicit in the selection process.

In conventional deterministic capacity expansion studies, the problem generally is simplified by specifying a desired level of power system reliability, and then setting the environmental and socio-economic objectives as constraints which define limits on the range of possible solutions. This simplification avoids the solution of a complex multi-objective decision problem.

3.2.3. Dynamic nature of the planning problem

The decisions taken at each time step will modify the characteristics of the system through: the retirement of old units; the addition of new units; and different management of the system. In other words, the planning problem is dynamic in character.

This strong dynamic character, as well as the fact that the characteristics of the system and its environment will be affected by inherent uncertainties, is further complicated by the incompatibility usually existing among the multiple objectives guiding the selection process. The practical difficulties in eliciting the decision maker's preferences indicate the need for replacing or complementing the conventional mathematical formulation of the problem, which usually is based on the principle of optimisation (i.e. maximising or minimising an objective function), with other decision criteria based on the principle of satisfaction (i.e. assuring that the outcomes will satisfy certain preferences of the decision maker and IAPs). All of the above means that analysis should be thorough in order to allow the decision maker to choose a solution that will, insofar as possible, be robust and acceptable under all feasible outcomes of the uncertainties [1].

3.3. Identify the problems and set up the goals

The ultimate goal of decision makers is to improve the situation in the future by solving, at least partly, the problems existing today. Therefore, the first step in decision making is to identify the problems to be solved. This task essentially is performed by decision makers and IAPs, in close co-operation. However, analysts may provide support by making available documented information on the current situation and its possible evolution, as a means to show the future evolution of the problem in a 'no action' scenario.

In order to understand better the current problems, it is important to examine the historic development and to analyse the social, political, economic and technical context which led to the present situation. A preliminary assessment of future trends might be carried out to illustrate the consequences of keeping the power sector unchanged, i.e. taking no action on either the supply or demand side, over a given period of time. The analysis should provide indications about the importance of implementing a proper solution to a specific problem, by highlighting the consequences of a 'business as usual/no action' strategy.

The analysis is concluded when the participants in the process are convinced that the essential information has been used to build up a satisfactory causal network that characterises the problem situation and highlights the main cause-effect relationships. The different aspects, causes and effects of the problem should be described precisely and, insofar as feasible, quantified. Setting up qualitative and quantitative indicators is essential for further evaluation and for monitoring of the effectiveness of implemented measures aiming towards alleviating or mitigating the problem.

The decision makers set up the specific goals, at a given time and in a given socio-economic context, taking into account the problems to be solved and the overall policy framework within which the electricity system is operated. In a number of cases, these goals might be conflicting. For example, economic growth might call for low electricity prices, while reducing environmental burdens would lead to increased electricity generation costs and, therefore, higher prices. In many cases, decision support studies will require the use of multi-objective approaches (see Chapter 4).

3.4. Define quantifiable evaluation criteria and planning objectives

The task which is formulated by the decision maker will require further clarification before analysis can begin. The *goals* of the decision maker have to be defined in terms of quantifiable *evaluation criteria and planning objectives*. Some examples of quantifiable objectives (e.g. minimise long-term costs, enhance the financial flexibility, etc.) of electricity system analysis can be found in Annex VI, Corporate Integrated Resource Planning (CIRP). The objectives of the decision will determine the objectives and limits of the analysis.

The objectives and limits of decision support studies should be defined clearly and precisely from the outset, in order to identify key issues to be addressed, focus the work, and avoid wasted efforts. Defining the objectives of a study essentially means answering the question: 'What should be achieved through the analysis?'. There are many possible objectives, falling within two main categories: direct support to decision making; and explanatory analysis for policy purposes. Within the first category, examples of objectives might be to: develop the least cost electricity system expansion plan; develop an electricity system expansion plan that minimises greenhouse gas emissions; determine the required capital expenditures for an electricity utility over a period of twenty years. The second category aims at enhancing the understanding of the existing electricity system in order to facilitate further policy formulation. Examples of objectives in this second category are to: characterise and quantify environmental impacts from the electricity sector; establish mathematical correlations between economic indicators and electricity demand as a basis for projecting future trends.

The evaluation criteria are the measures of the merit of an option or a strategy referring to an objective: cost of electricity, earnings per share, loss of load expectation, etc. Usually the task is to minimise or maximise the measure of merit, or to keep it above or below a given limiting value [2].

The detailed specification of the objectives offers the major advantage of providing agreed upon and quantifiable criteria that can be used in the evaluation of the various options. Clearly and properly specified objectives help to guide the evaluation by indicating the types of data that have to be collected, the analyses to be performed, and the indicators (output parameters and their range of values) which would be accepted, by decision makers and IAPs, as evidence of the degree of success in meeting the objectives with different options and strategies.

The objectives can be specified further by sub-objectives, from which assessment criteria can be identified. An example of a sub-objective is: ‘enhance the utility’s financial flexibility’, and the associated criteria are ‘net income’ and ‘debt ratio’ of the utility under various scenarios. Another example is: ‘enhance the welfare of local communities’ and the associated criteria are ‘changes in regional and local employment’ and ‘economic benefit to the community’.

3.5. Specify scope, boundaries and analytical approach

Specifying the scope and boundaries of the study means defining its:

- geographical coverage, e.g. specific project, local or regional network;
- time horizon: e.g. one year with fine (daily/weekly) time resolution; medium term (up to ten years) with monthly or quarter-year time resolution; or long term (20 to 30 years or more) with yearly resolution;
- sector coverage, e.g. power plant, electricity sector, energy system; and
- level of technical and economic detail, e.g. ‘quick and dirty’ screening analysis or in-depth optimisation.

The reference energy system (RES) technique can be used to represent the scope of a case study and the boundaries of the system to be analysed. The RES diagram, as shown on Figure 3.3, provides a graphical representation of the entire energy network considered, including conversion nodes and material flows from primary energy source extraction (or delivery at the boundary of the system), through transport, processing and electricity generation, to final service delivery.

Different approaches can be adopted for carrying out a decision support study. The choice of approach is driven by the type, scope and boundaries of the study. Basically, there are four main types of approaches: project evaluation, full energy chain analysis (FENCH), life cycle analysis (LCA) and energy network analysis (system analysis). All of these approaches may provide, according to their level of sophistication, more or less detailed analysis of environmental burdens arising from electricity generation.

Project evaluation is a detailed analysis of one specific project. For example, the project considered might be the rehabilitation of an existing coal fired power plant to enhance its efficiency or reduce its atmospheric emissions in order to meet new regulations. Another example might be the construction of a new power plant for meeting demand growth in a given region of a country. The project evaluation should analyse all the aspects and consequences that are relevant to the scope of the study. This might include capital investments, consequences at the electricity system network level, environmental impacts, and broad macroeconomic impacts.

Life cycle analysis (LCA) and the full energy chain (FENCH) approach are two variants of a procedure aiming towards comprehensive investigation of different aspects of alternative energy chains for comparative assessment purposes. Figure 3.4 illustrates these two concepts and shows their main common features and differences. In both cases, energy chains are described by their successive steps, from primary source extraction, through processing, transport and conversion, to electricity delivery to customers. The analysis covers energy and material flow as well as emissions, residuals and wastes arising. Figure 3.5 shows an example of the energy chain for coal electricity generation, embedded within the RES diagram.

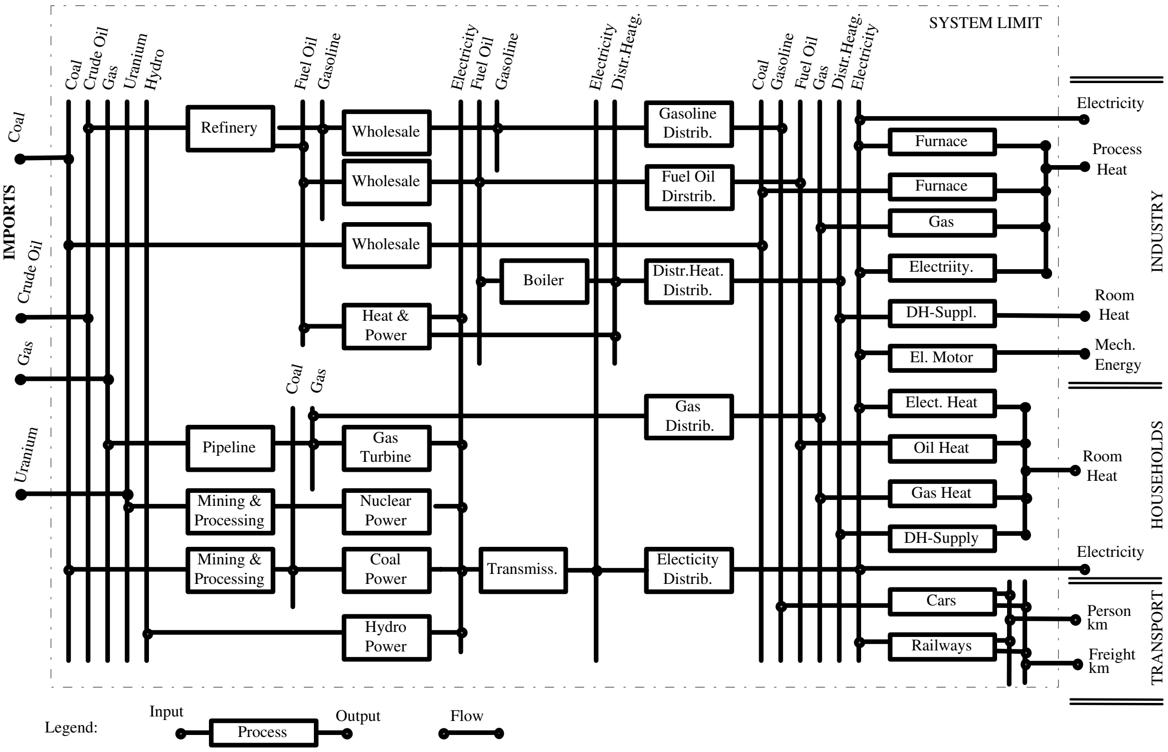


FIG. 3.3. Example of reference energy system (RES) diagram.

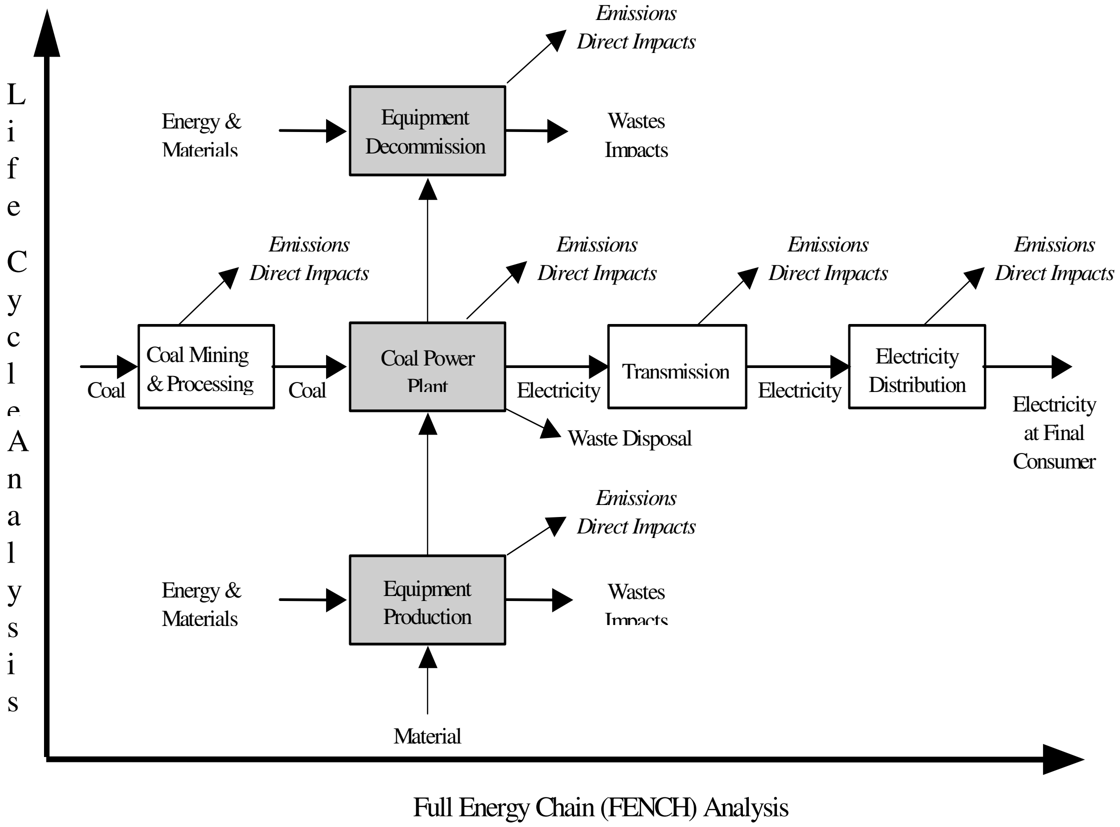


FIG. 3.4. Schematic comparison of life cycle analysis (LCA) and full energy chain (FENCH) analysis.

Full energy chain (FENCH) analysis considers the energy and material flows, and the emissions, residuals and waste arisings, within the entire electricity generation chain from the resource level to the delivered energy service level. This allows to account and compare economics, material requirements and environmental aspects of alternative options that supply similar services to the final user. The FENCH approach focuses on the requirements and impacts associated with the construction and operation of the facilities constituting energy chains, but generally does not include ‘second order’ effects associated with the production of construction materials, etc. The Reference Technology Data Base (RTDB) and its associated integrated software package (DECPAC), developed by the IAEA within the DECADES project, is one example of computer tools for full energy chain analysis [3].

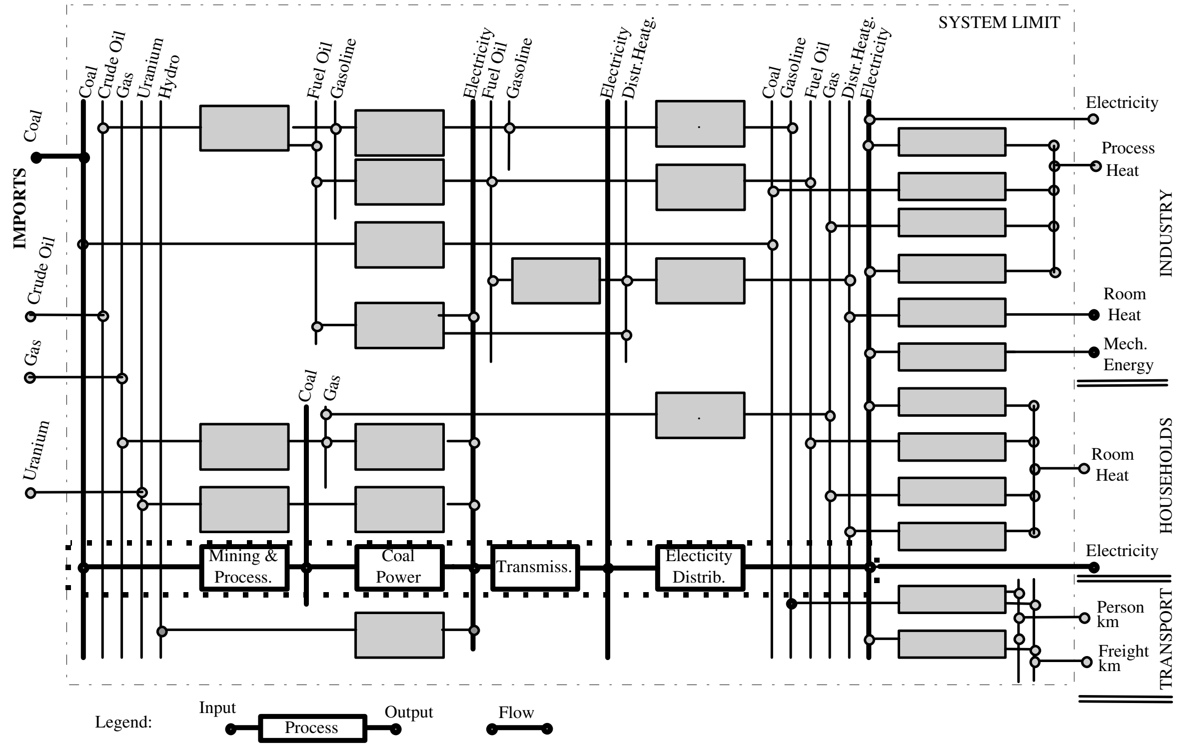


FIG. 3.5. Coal electricity generation chain embedded in the RES diagram.

Life cycle analysis (LCA) subsumes FENCH analysis together with an accounting of ‘second order’ effects associated with the production of materials (e.g. plastics, steels) used in equipment and construction, transportation of these materials, etc., for all the facilities, equipment and operations constituting an energy chain. LCA embodies the concept ‘from cradle to grave’ which implies, in principle, that all energy and material flows that contribute to electricity generation are accounted for and that all associated environmental burdens are estimated and reflected in the overall assessment of the chain. The Environmental Manual for Power (EMP) software [4], developed by the Öko Institute (Germany) together with the Gesellsschaft für Technologie und Zusammenarbeit (GTZ - Company for Technology and Co-operation, Germany) within a multinational project managed by the World Bank, is an example of LCA tools that offer capabilities for analysing emissions and residuals arising from different electricity supply technologies.

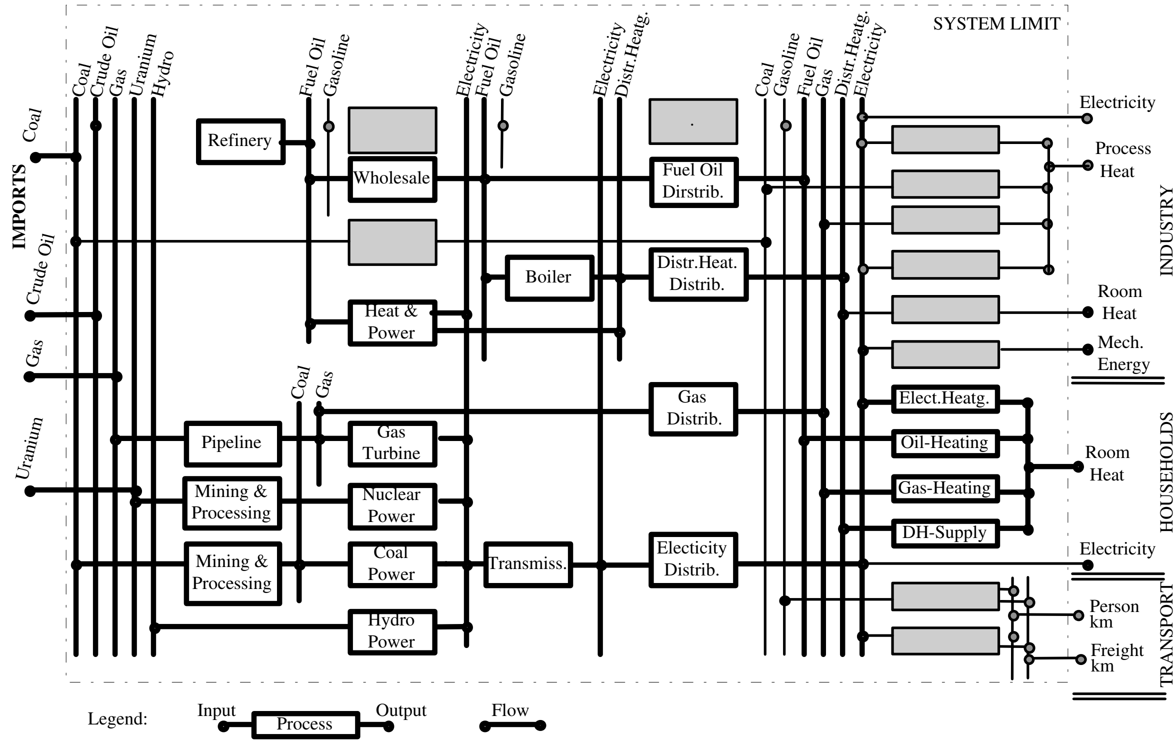


FIG. 3.6. Room heating network as an example of the scope of network analysis.

Energy network analysis (system analysis) considers, within an integrated framework, all the interlinked energy chains providing services to users. Network analysis addresses energy and material flows throughout the energy system, together with the resulting emissions, residuals and wastes. Figure 3.6 illustrates the concept of network analysis applied to a system for providing room heating.

Models and computer tools that can support network analysis should allow to calculate all energy and material flows, emissions, residuals and waste arisings of competing energy chains that can provide similar end-use service. Such an analysis includes the assessment and comparison of different technology paths according to multiple criteria: cost, energy balance, environmental pollution, resource consumption, etc. The ENPEP model developed by the IAEA and the Argonne National Laboratory (ANL/USA) is one example of computer tools for network analysis [5]. The IAEA's DECPAC electricity system analysis software allows to carry out detailed network analysis limited to the electricity system [3].

3.6. Define frame data

A large number of data are required to carry out a decision support study and perform a series of investigations in the context of different futures and alternative strategies (see section 3.7 on design strategies and define possible futures). The so called ‘frame data’ describe the overall context, constraints, assumptions and agreements that are binding for all parts of a given study. They include exogenous assumptions that are not modified during the study. Defining the frame data in a co-ordinated way, through the work of an interdisciplinary team of experts, is essential in order to allow a sound comparative assessment of alternative options and strategies.

Frame data related to the context of the study include the characteristics of the existing electricity system, and macro-economic, energy and environmental parameters of the base year. These data describing the actual situation are, by definition, not under the control of the analysts nor of the decision makers and constitute a ‘frame’ within which alternative futures should be analysed and compared.

Basic assumptions agreed upon when setting up the objectives, framework, scope and boundaries of the study are also part of the frame data. They include parameters such as discount rate, base year and horizon, regional aggregation, territorial boundaries, number and types of fuels, supply sectors and demand sectors considered, and basis for economic comparisons (e.g. levelised costs in constant US$ of the base year).

The values adopted for basic assumptions within the frame data should be consistent with the context of the study (e.g. economic assumptions reflecting the conditions prevailing in the country or region considered) and with its objective (e.g. time horizon in line with the purpose - operational or strategic - of the exercise). Whenever relevant (e.g. for discount rate), the frame data values should be discussed and agreed upon between the different actors in the decision making process.

3.7. Design strategies and define possible futures

In order to solve a specific problem and to meet policy goals, a number of options and measures are available, on both the supply side (e.g. building new plants and/or retrofitting existing plants) and the demand side (e.g. more efficient end-use devices), as ‘candidates’ for alleviating and/or mitigating undesirable impacts. During the formulation of the planning task, one of the most important steps is the identification of the candidates to be included in the analysis, and to define their main characteristics. These candidates can be combined in different ways to form ‘strategies’. The design of alternative strategies should aim towards investigating a wide range of feasible paths in order to provide decision makers with comprehensive information upon which relevant choices can be based.

The development of electricity systems is characterised, as pointed out in the introduction, by a wide range of uncertainties (e.g. load growth rates, fuel prices, regulatory changes, etc.) that are beyond the planner’s or decision maker’s complete foreknowledge or control. These uncertainties have to be characterised by parameters representing the likelihood of certain outcomes; for example, a 90% likelihood that the load growth rate will be 3% per year or higher. In order to determine the influence of uncertainties on the results of the analysis, it is necessary to explore a range of values for the parameters that have the greatest influence on the solution obtained. This generally is done by defining possible ‘futures’, each of which is characterised by an assumption for one of the main influencing uncertainties. Different futures have to be defined, corresponding to a range of expected values for the different uncertainties. The assumptions underlying a given future should remain constant throughout the process for all calculations carried out. The values chosen as ‘future’ parameters, such as prices of imported energy on the world market, should be discussed and agreed upon by the different actors in the policy making process.

The strategies and futures analysed will, in most cases, lead to different electric sector development paths and investment levels. The purpose of the strategies is to represent specific ways that one or more objectives could be achieved and to provide a basis for assessing and evaluating the impacts of investment directions. Trade-off analysis [6] (see Figure 3.7) allows to investigate a number of possible strategies regarding the electricity system being analysed and eventually to

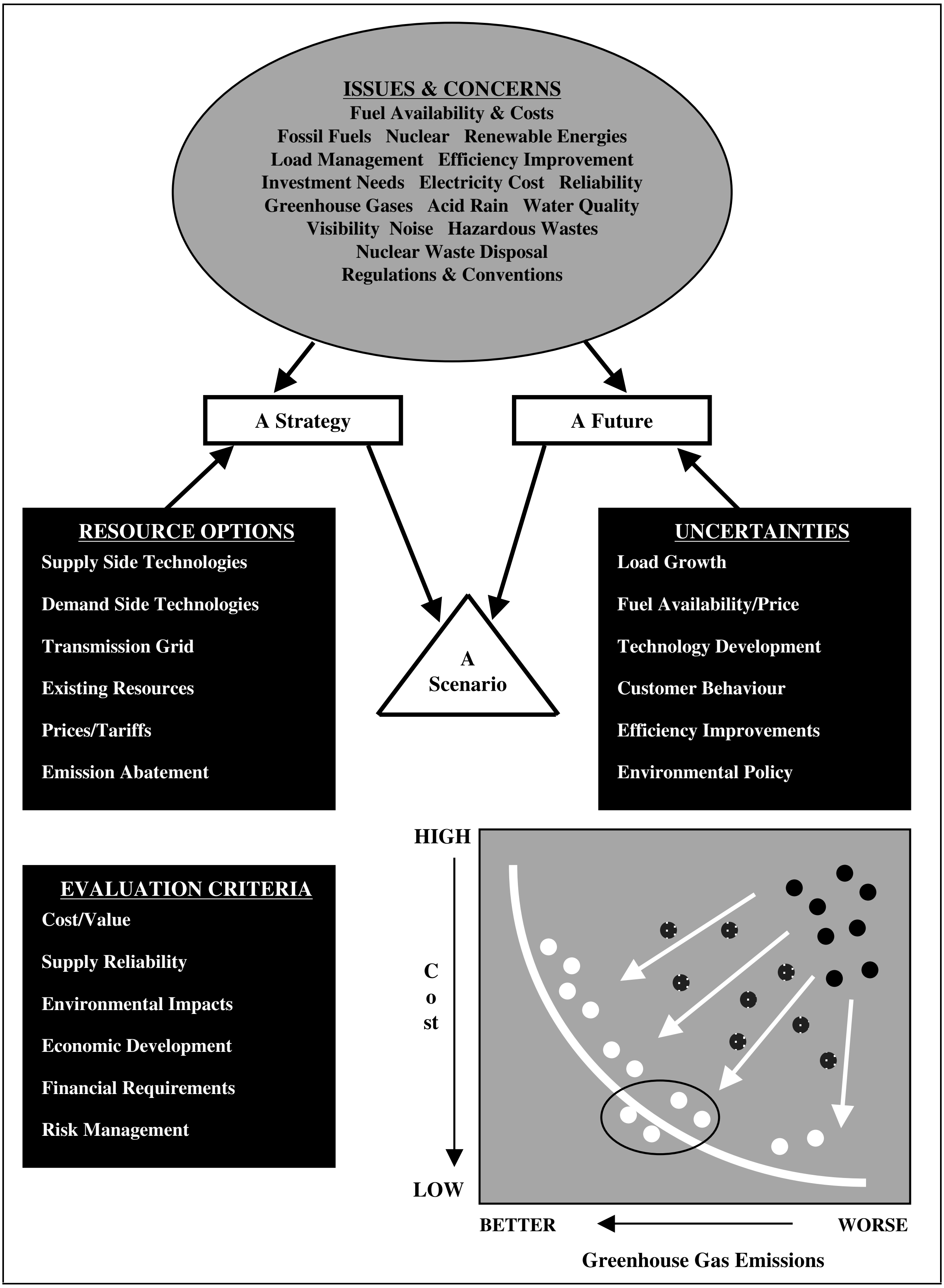


FIG. 3.7. The procedure of trade-off analysis.

identify ‘robust’ strategies (i.e. sets of actions and measures) that, under most circumstances within the uncertainty range, will nearly meet the optimisation criteria.

Figure 3.8 shows an example in which two types of futures are considered, that are characterised mainly by high and low economic growth, called ‘prosperity’ and ‘stagnation’, respectively. In this example, the combination of two futures with three strategies produces six scenarios, or cases, to be evaluated.

In the ‘prosperity’ future, the assumed overall economic growth is associated with steady increase in industrial production and private household income. For the electricity sector, the prosperity scenario entails increasing demand for services and allows for steady penetration of advanced technologies including ‘clean’ electricity generation options. Also, higher income rates facilitate the implementation of economic policy measures (e.g. taxes on emissions) for reducing emissions and other environmental burdens. In the illustrative case, real world energy prices are assumed to be constant in real terms (i.e. no price increase above general inflation).

In ‘stagnation’, with economic growth being lower, technology changes are implemented more slowly and the overall efficiency of the energy/electricity system is not enhanced drastically. Environmental issues tend to have a lower priority, in light of the social impacts of low income rates, and measures to promote new technologies are more difficult to implement.

Strategies are designed by the analysts, having in mind the problems to be solved and the expected priorities of decision makers. Usually, each strategy is designed to address mainly one issue or problem, e.g. environmental burdens or economic competitiveness. For example, a strategy focusing on reducing the risk of global climate change might include measures such as: subsidising the implementation of ‘greenhouse-gas-free’ technologies; imposing carbon taxes; and setting carbon dioxide emission limits. A strategy aiming at enhancing energy efficiency might include: subsidising energy saving measures; carrying out information campaigns on energy conservation; and imposing energy taxes. The results illustrate ‘what if’ outcomes; that is, what would be the results if a given strategy would be implemented. Their comparison allows to identify benefits and drawbacks of alternative strategies within a given scenario. In order to establish a reference for evaluating the different strategies, it is strongly advised to analyse a ‘Business as Usual (BAU)’ strategy, which examines what would happen if no explicit actions would be taken to address the issues or problems.

The planning process translates concerns into evaluation criteria, options and uncertainties. Options are combined into strategies and uncertainties into futures. Strategies and futures are combined into scenarios. Each scenario is evaluated against the criteria and analysed using trade-off analysis.

3.8. Select methodologies and tools

There are a number of methodologies, analytical models and computer tools that can be used in support of electricity system analysis for decision making purpose. Models and computer tools allow to address complex issues and to deal with conflicting objectives within a reasonable time frame and with acceptable manpower effort. Selecting adequate tools is a prerequisite to carry out efficiently a study and to obtain relevant and reliable results. The analytical tool must be adapted to the scope of the study, its boundaries, the approach chosen and to the data, time and manpower available to the planning team. While a simplistic approach is likely to provide weak results, choosing an exceedingly sophisticated methodology is likely to overly complicate the work with only marginal, if any, enhancement of the quality of the results.

The selection of analytical tools is made somewhat difficult by the lack of comprehensive information on the available tools and by the number of criteria to be taken into account. It is important, when assessing the relevance of different models for a given study, to be aware that models generally have been designed for a specific purpose and that their use for other purposes might be difficult or even not appropriate at all.

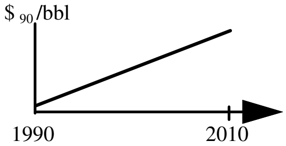
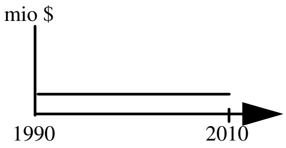
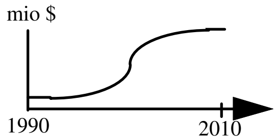
	Frame Data						
	scenario						
S c e n a r i o P a r a m e t e r s	crude oil price						
	industrial prod.						
	strategy	**Business as Usual**	**Taxes**	**Technical Standards**	**Business as Usual**	**Taxes**	**Technical Standards**
M e a s u r e s	CO_2 tax	none	x $\frac{\$}{t_{CO_2}}$	none	none	y $\frac{\$}{t_{CO_2}}$	none
	subsidies for solar facilities	none	20% investment subsidy	none	none	40% investment subsidy	none
	shutdown of old facilities (boiler)	no	if older than 30 years	if efficiency lower than 30%	none	if older than 25 years	if efficiency lower than 90%
	regulations for each kind of boiler	no	no	over 300 MW_{th}	none	none	over 200 MW_{th}

FIG. 3.8. Illustrative example of 'stagnation' and 'prosperity' scenarios, together with different strategies.

Models have been designed and implemented to serve many diverse purposes; therefore, there are many ways to classify them. Although there are some documents [7] providing information on models and computer tools for energy/electricity system analysis, a complete overview of the models available world-wide does not exist. Selection criteria for choosing computer tools should include aspects such as: user friendliness of the software, availability and quality of the user's manual, access to training if necessary, computer storage and performance requirements, and data intensity. Annex I deals with issues related to the selection and use of models for electricity system analysis and gives a non-exhaustive list of relevant computer tools running on PCs and that are available at very low or no cost.

In most cases, as mentioned in previous sections, several tools will be required to carry out a study. Decision support studies should be based upon an integrated approach covering all aspects of resource and impact assessment as well as energy/electricity system analysis. Unfortunately, most models available have been designed for dealing primarily with one aspect, e.g. power system expansion planning or demand side management. In this context, the choice of a methodological approach includes selecting and bringing together a number of specialised models and tools in an integrated framework (computer model network) which is capable of simulating the present and possible future behaviour of the whole system being analysed and to provide results on relevant economic, social, health and environmental aspects of the different scenarios and strategies considered.

3.9. Collect data and conduct analysis

Data requirements for carrying out the study depends on its scope and objectives and on the methodology and computer tools selected for the analysis. The RES diagram may help to identify the required data through identifying for each box (process) and for each link (commodity line) of the diagram the necessary characteristics and data that have to be collected. At the boundaries of the RES, quantities and prices of inputs and outputs should be specified whenever relevant.

Generally, data collection and consistency checking is time and manpower intensive. Statistical, technical, economic and other information can be drawn from existing databases and from statistical offices, utilities, governmental bodies and scientific institutions. If necessary, missing data can be either estimated or collected through surveys undertaken specifically for the study. The data collection process should be adapted to the time and budget allocated for the study. Data consistency and quality have a major impact on the reliability of the results. The data collection process should be seen as a continuous activity in the dynamic perspective of an iterative analysis and decision making process. If the collected data are stored, managed and updated systematically, each iteration of the process will improve the quality of the data and complement the information base, making it easier to carry out the next study and allowing to provide decision makers with enhanced results. A key point is that missing or unreliable data cannot be used as an excuse for inaction, but rather as an incentive for taking further action to fill the gaps and to improve the reliability in the data.

Conducting the analysis is a significant undertaking that covers, besides data collection, a series of step by step studies addressing issues related to demand, supply and impact assessment. Furthermore, interim results have to be evaluated and, in most cases, a number of iterations are necessary in order to complete a consistent study. The overall procedure is described in Chapter 4.

The same sequence is repeated for all cases. A preliminary analysis and comparison of results corresponding to each case allows: to identify ‘preferred strategies’ that would provide reasonably good solutions to the problems; and, within a given strategy, to indicate which actions and measures might need to be modified or adapted in order to enhance its efficiency in solving the problems. The preliminary findings serve as a basis for further iterations aiming towards finding ‘robust’ solutions.

The iterations are supported by means of: sensitivity analysis to test the internal stability of a strategy when single actions and measures are modified; and parameter variations that allow to assess the relative efficiency of alternative strategies under a range of possible ‘futures’. The sensitivity analysis simulates the impact of modifying a given strategy measure or action on the indicators characterising the evolution of the system. A sensitivity analysis may be carried out, for example, on the appropriate level of carbon taxes within a ‘stagnation future/tax strategy’ scenario. The results from such a sensitivity analysis would help in assessing and comparing different tax levels with regard to their: efficiency (i.e. emission reduction obtained); cost (i.e. increase in electricity generation cost); and impact on technology choices (i.e. impact on the respective share of different supply technologies). Sensitivity analysis has also the objective of assessing how much the results would be changed by modifying one measure or action. For example, a sensitivity study might be carried out to determine whether drastic reduction of sulphur dioxide emission limits would increase significantly, or not, the cost of electricity generation.

Parameter variations are performed by modifying either a future parameter or a strategy measure for all the cases or scenarios considered. Variations of future parameters allow to compare the capability of different strategies to cope with different evolution of exogenous factors such as oil prices on international markets. Variations of strategy measures and actions allow to search for an optimum, for a given measure or action, irrespective of the scenarios and strategies considered.

A ‘robust’ solution has been identified when a strategy is found to provide acceptable results under most evolution paths for exogenous future parameters (within the range considered). It should be pointed out that, in most cases, the outcomes from the first pass through the analysis process will not identify a solution that is robust for all criteria. Therefore, it is the task of the planner to follow the described iterative procedure in order to find eventually a robust solution.

The time and manpower necessary for collecting data and conducting the analysis may vary significantly from study to study, depending on its scope and objectives, on the size of the system to be analysed and on the level of detail required by decision makers. While an ad-hoc study, focusing on a limited number of key issues, may be carried out within some days (by a team having already collected relevant data for previous studies and having experience in running appropriate models), an in-depth analysis of a complex system addressing economic, social, health and environmental aspects may require a year or more.

An indicative schedule for a complete study, from identification of problems to presentation of results, is shown on Figure 3.9. Since, as mentioned above, the actual schedule for a given study will be influenced by a number of factors, the figure is for illustrative purpose only, and is presented mainly to point out the sequence of tasks and the approximate time required for each.

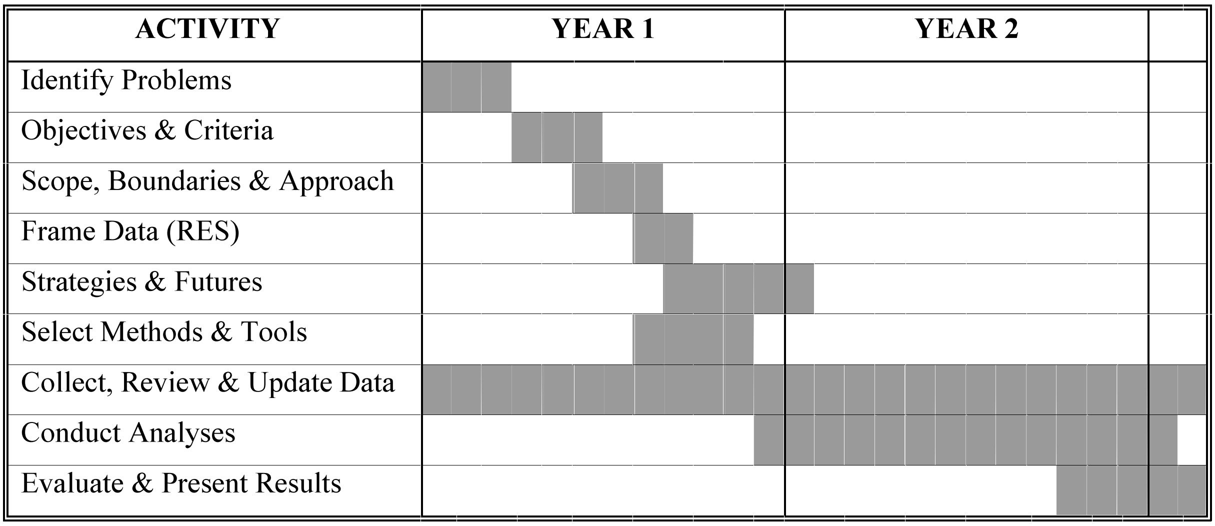


FIG. 3.9. Illustrative example of the steps and schedule for a decision support study.

3.10. Evaluate and present the results

The analytical study provides a systematic comparative assessment of the consequences (costs, benefits, impacts and risks) of alternative strategies under different futures. For decision making purposes, these results need to be evaluated and presented as a coherent plan, i.e. a set of concrete actions and measures that would solve the problem(s) identified. The evaluation and presentation of the results should focus on identifying robust solutions and pointing out the main findings and conclusions that could support decision taking.

Evaluating the results is essential in order to ensure the consistency and reliability of the information provided to decision makers. This is especially necessary when the results have been obtained through a series of specific analyses focusing on different issues and relying on the use of various methodologies and computer tools. It should be stressed that, for carrying out this key task, the analyst team has to rely on its know-how and experience, since mathematical tools cannot replace expert judgement for that purpose.

The presentation of the results has to be adapted to the target audience of the study. Generally, the primary audience will be decision makers, e.g. in a governmental body or electricity utility board. However, in most cases, the study also will be disseminated to, and used by, interested and affected parties, e.g. local communities or NGOs. In both cases, the audience has not the same experience and knowledge on technical and economic issues as do the analysts. Therefore, results should be presented clearly and concisely, pointing out the main findings and outcomes.

In order to assist decision makers effectively, analysts should present their results in a transparent manner, focusing on the objective results and avoiding subjective interpretations. In particular: input data and assumptions should be specified clearly and the boundaries and limits of the study should be indicated; and comparisons of alternatives should be based upon indicators that have been estimated qualitatively, or preferably quantitatively, through the analysis.

The results should be presented in the form of an 'action plan' translating a strategy that the analysis shows to be adequate into an agenda of actions and measures that could be implemented by the decision maker, taking into account exogenous constraints such as financing, resource availability or public acceptance. The action plan proposed to decision makers should be technically and financially feasible, publicly acceptable, and fit into the legal, economic, and social framework within which it would be implemented. The plan should state when to initiate and how to implement the different actions and measures that constitute a given strategy. For example, results from a least cost strategic planning study at the utility level would be translated into an action plan providing yearly investment and cash flow requirements. An action plan at the national level might include the timing for imposing energy or carbon taxes and their specific (e.g. US$ per tonne of carbon dioxide emitted) and total (e.g. millions of US$ per year) amounts.

Win/win solutions seldom are provided by analytical studies, because they seldom exist. Therefore, in most cases, the presentation of results should highlight the advantages and drawbacks of different strategies in order that decision makers, and IAPs, could choose the trade-offs according to their priorities (see Chapter 5).

The outcomes of a decision support study should provide also a basis for implementing a monitoring system that allows to identify and, insofar as feasible, measure quantitatively the actual impacts of the actions taken, and to compare these with the values that had been estimated. Monitoring the efficiency of a strategy helps in identifying new or unsolved problems, and the comparison with estimates shows where there is need for more analysis and iteration of the process. The monitoring system gives also the possibility to detect unexpected developments and to take remedial actions.

REFERENCES TO CHAPTER 3

[1] CASTILLO BONET, M., "Dealing with Uncertainty in Integrated Electricity Planning", in Integrated Electricity Resource Planning (de Almeida, A.T., et al., Eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands (1994).

[2] CROUSILLAT, E.O., DÖRFNER, P., ALVARADO, P. AND MERRILL, H.M., "Conflicting Objectives and Risk in Power System Planning", IEEE Transactions on Power Systems, vol. 8, No. 3 (August 1993).

[3] VLADU, I.F., "Energy Chain Analysis for Comparative Assessment in the Power Sector", in Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making (Proc. Int. Symp., Vienna, 16-19 October 1995), IAEA Proceedings Series, STI/PUB/975, IAEA, Vienna (1996).

[4] WORLD BANK, GTZ, ÖKO-INSTITUTE, The Environmental Manual for Power Development, An Introduction to the EM Version 1.0, Darmstatt (1995).

[5] HAMILTON, B., et. al., Energy and Power Evaluation Program (ENPEP) Documentation and User's Manual, Report ANL/EES-TM-317 Rev. 1 (September 1994), Argonne National Laboratory, Chicago (1994).

[6] TENNESSEE VALLEY AUTHORITY, Energy Vision 2020 - An Integrated Resource Plan and Programmatic Environmental Impact Statement, Chattanooga, Tennessee (1995)

[7] SCHRATTENHOLZER, L., Assessment of Personal Computer Models for Energy Planning in Developing Countries, World Bank, Washington, DC (1991).

CHAPTER 4

AN INTEGRATED APPROACH TO ENHANCED ELECTRICITY SYSTEM ANALYSIS

4.1. Introduction

This chapter describes the necessary components of an integrated approach for consideration of the economic, social, health and environmental effects in decision making for the electric sector, as shown in Figure 4.1 (the number at the bottom of the box refers to the section in this chapter where the subject is discussed). The ultimate outcome from this approach is comparative assessment information that supports the formation of an action plan, for consideration by decision makers and IAPs.

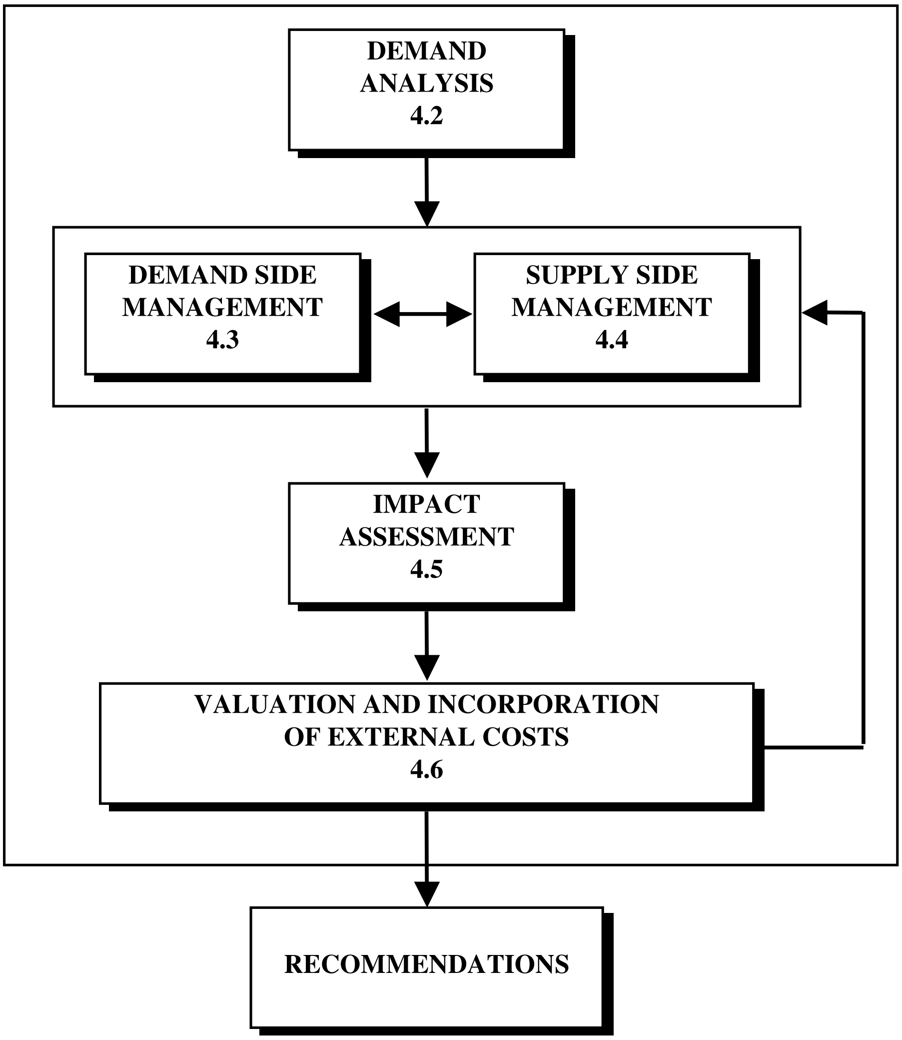


FIG. 4.1. The integrated approach to energy system analysis.

The components include demand analysis, demand side management, supply side management, impact assessment, valuation and incorporation of external costs. Primary characteristics of each component are described, but a complete description of specific analytical approaches for each component is beyond the scope of this chapter. Therefore, the interested reader is encouraged to explore the topics further by examining the cited references and the documents listed in the bibliography (Annex X).

The framework shown in Figure 4.1 is not entirely new. It has been used, at least in part, for studies conducted even some years ago. However, the relative amount of effort devoted to demand analysis and demand side management, and in particular to the valuation and incorporation of external costs, generally was much less than is needed today. The problem was primarily to estimate the demand and determine the least-cost combination of supply options to meet that demand, within reliability, environmental, financial and other constraints, typically as seen from an electrical utility viewpoint [1]. For example, if generating plants met regulatory standards for emissions, the utility had no incentive to incur costs to reduce emissions further. However, the need to consider costs and impacts of electric utility decisions beyond a narrow electrical utility viewpoint was evident already. Integrated frameworks were developed that recognised impacts that were of concern at several different geographical levels, which may result in different levels of potential policy interest and intervention, e.g. global, international, national, regional and local [1, 2, 3, 4, 5, 6, 7].

As regulatory bodies and the public became more involved in electric utility decisions, the term *integrated resource planning* (IRP) was used to describe a planning methodology that aimed towards meeting reliably the demand for energy services with minimum societal costs, by optimising the mix of supply-side and demand-side options and taking into account externalities, such as health and environmental impacts [8]. The definition of the boundaries within which IRP operates has varied among different studies. The integrated approach described in this chapter conceptually addresses a broad framework of the complete electrical energy system and its associated fuel supply system and is not bounded by national or regional borders. For example, the emissions throughout the energy chains for electricity generation are included, even though some emissions may occur outside the national borders (e.g. for the production of imported fuels).

The goal of the integrated approach is not to combine all considerations into a single criterion (e.g. monetary value). Instead, the goal is to provide: a foundation of data and appropriate methods of analysis; a matrix of performance measures (e.g. cost, reliability, safety, health and environmental impacts, estimates of externality costs), and a consistent framework for evaluation, including placing value judgements on the different performance measures. The approach is intended to be objective and open to scrutiny, and to make the advantages and disadvantages of various technology options and electricity supply strategies readily apparent.

An important factor in each application of the framework is the development of qualitative and quantitative thinking about value judgements prior to full development of data bases, analysis of demand-side and supply-side options, impact analysis and integration. Early emphasis on the value judgement part of the problem can help in determining what should be modelled and what types of models are appropriate, and also may help in designing different alternatives for evaluation [9].

Some modelling approaches use a step-by-step procedure to address the series of tasks shown in Figure 4.1. In this procedure, a number of models, which may be linked in order to share common data and to exchange results, typically are applied in a sequential analysis. Other approaches, that attempt to incorporate most of the considerations shown in Figure 4.1 in a single model, have been developed. In this procedure, the entire sequence of steps is analysed in one modelling run. The exact form of the information that has to be collected, and the detail needed in the modelling approach, depends on the particular situation being examined and the character and urgency of the problem being addressed. An analysis such as portrayed in Figure 4.1 may require a year or more for completion, if the relevant models and supporting data are not available already; on the other hand, once the models and data have been established and tested, then meaningful studies can be conducted in as little as a few hours or days.

The following sections describe key considerations in each component of the integrated approach shown in Figure 4.1. Special emphasis has been placed on those areas upon which attention has focused in recent years, such as demand side management, special considerations in expansion planning for predominantly hydro systems, evaluation of external costs, and methods for overall evaluation.

4.2. Demand analysis

4.2.1. General aspects

Electricity demand analysis is an attempt to forecast the future demands for the services that electricity provides, and to estimate how much electricity will be needed to provide those services. The size and structure of the economy, the prices of competing energy forms, and the evolving cost and performance of energy-using equipment are key elements in the demand forecasting process. Government policies (e.g. taxes) and utility activities (e.g. promoting energy efficient appliances) also could alter the energy choices made by consumers, thereby influencing the demands for primary energy and electricity.

A balanced perspective is needed in order to formulate realistic long term electricity demand forecasts. This requires careful examination of the historical economic growth and electrical intensity patterns, in order to separate cyclical and transitory elements from the factors that are the fundamental determinants (i.e. 'drivers') of the long term electricity demand growth. In order to understand some of the differences between long term trends and short term variations, it is useful to review how demand has evolved in the past over both the long and short term.

The most important factors in the determination of the demand for electricity are: the economic activity level; the prices of electricity and competing energy forms; and the performance, price and market saturation level of energy-using equipment. Broadly speaking, the future level of economic activity is a major driver of future demand for energy services. Energy price variables influence the customers' choices regarding energy form (e.g. electricity versus direct use of fuels) and level of utilisation [10]. The future stock of energy-using equipment is highly determined by their performance, price, market saturation level and turnover rate, as well as by the prices of different energy forms.

The electricity intensity (i.e. units of electricity used per unit of 'productivity') is used widely for checking the consistency of assumptions applied and results obtained in electricity demand forecasting. For example, the amount of electricity consumed (in kilowatt-hours) per constant monetary unit of real Gross Domestic Product (GDP) is a measure of the electricity intensity of the economy, and this is an important driver of the electricity demand forecast. Electricity intensity of the economy changes whenever electricity consumption grows at a rate different from the growth in the economy. Some important contributors to changing electricity intensity are: the choices by made by customers (often driven by price) to use electricity rather than other energy forms (e.g. using electricity rather than gas for heating or cooking); to change electricity service levels where electricity has no substitutes (e.g. using less air conditioning in order to reduce costs); and to change the efficiency with which electricity is used (e.g. by purchasing energy efficient light bulbs). Shifts in the mix of economic activities may also have a significant impact on electricity intensity. The electricity intensity, and its evolution over time, can differ dramatically from country to country depending on the structure of the economy, efficiency of electricity usage, lifestyle, etc.

The implementation of a sound electricity demand forecasting procedure can be an expensive, time-consuming exercise depending on the nature of the task. Several different steps have to be carried out, as illustrated in Figure 4.2 [11]. The economic analysis has to cover, inter alia: the present status and expected future development of different sectors of the economy (e.g. industrial, commercial, residential); population growth trends; customer characteristics; and prices of different energy forms. The role of electricity demand forecasting is the determination of expected total electricity demand (e.g. in kW·h per year) by different customer groups or economic sectors, on the basis of the results from economic analysis. Having developed the forecast of total electricity demand, it is necessary to forecast the 'load curve', which indicates the peak load and the time distribution of loads (load shape) between peak load and minimum (or base) load, for each category of customer. This completes the first iteration of electricity demand forecasting. However, it must be kept in mind that the demand forecast is sensitive to the initial assumptions made on the price of electricity and competing energy forms, as well as to other factors that influence demand. Therefore, after the system level calculations have been completed, and projected electricity generation costs have been calculated, the consistency between the demand forecast, initial assumptions and estimated

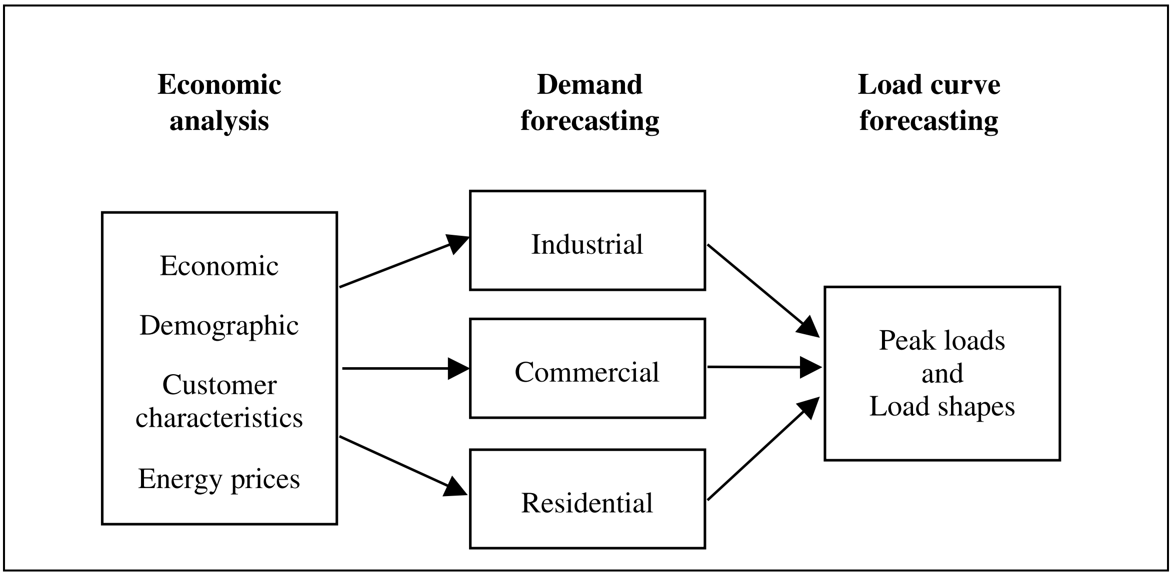


FIG. 4.2. The procedure of electricity demand forecasting.

costs has to be checked, and additional iterations may be required to reach a converged result that is consistent throughout.

4.2.2. Recognising uncertainty

Planning and implementing strategies to meet future electricity needs must recognise and adapt to the significant uncertainties, in both economic growth and electricity intensity, that surround the forecast of electricity demand to be met. This has been shown clearly in an evaluation [12] of forecasts in 45 countries (borrowers of the World Bank), which found that three out of four forecasts had over-estimated demand growth, whereas only one out of four had underestimated growth. Not surprisingly, deviation and uncertainty of the forecasts increased with longer time horizons.

A meaningful electricity supply plan must accept that large deviations from the base forecast, either lower or higher, may occur. In order to reflect the uncertainties in the electricity demand forecast, it is useful to develop a probability distribution for each year in the forecast period. Such a probability distribution would incorporate, for example, estimates of the probability for realising different levels of economic growth and energy efficiency improvements. The explicit treatment of uncertainties, and the probabilities of certain outcomes of demand growth, can assist in developing robust plans that are flexible enough to be nearly optimal under all outcomes.

Making forecasts of trends in the fundamental drivers of the long term electricity demand evolution is fraught with uncertainty. Electricity use pervades all aspects of the economy, and therefore its demand is sensitive to the scale and nature of the complete spectrum of economic activities. While some trends in the economy tend to remain stable over a rather long time span, others can be quite volatile. In addition, projecting electricity demand involves making predictions about choices customers will make, and that adds to the uncertainty.

4.2.3. Approaches to forecasting

The two main approaches that are widely used for long term electricity demand forecasting are ‘top-down’ and ‘bottom-up’ modelling. Both approaches attempt to capture the effect of a large number of demographic, economic, energy market and technological factors on electricity demand in the long term.

The ‘top-down’ approach relies on statistical analysis of past electricity consumption patterns and makes forecasts of broad economic trends as a means to develop estimates of future electricity demands. In the ‘bottom-up’ approach, the forecast is based on expert opinions of key technology and electricity market trends, combined with very detailed forecasts of the activity levels underlying the ways in which electricity is used.

The ‘top-down’ approach is capable of simulating macro-economic scenarios that result from different assumptions about key input variables, such as GDP and population growth. On the other hand, ‘bottom-up’ modelling may more readily identify significant changes in the demand trends due to technological development or shifts in the composition and levels of activities that use electricity.

The need for the electricity demand forecast to be tied to a broad scenario for the economy, and at the same time be sufficiently detailed to be useful for analysing demand management opportunities, can lead to a combination of the two approaches. In fact, as forecasting techniques have become more sophisticated, the distinction between the two approaches has diminished.

A number of models, ranging from the simple to the sophisticated, can be applied to electricity demand forecasting based on the above approaches. These models can be classified broadly into four groups:

- trend-judgement techniques
- econometric scenario simulation models
- end-use demand analysis models
- customer surveys (electricity market surveys).

The first two methodologies refer to the ‘top-down’ approach, while the latter two refer to the ‘bottom-up’ approach. The actual choice of methodology to be used for electricity demand forecasting is an important consideration, and the forecaster should be aware of the advantages and disadvantages of each methodology, based on the particular situation and needs. Criteria to be considered in selecting an approach include: the purpose of the forecast, data availability, forecasting horizon, and resources (cost, time and manpower) required for carrying out the forecast.

The use of multiple forecasting models makes it possible to avoid the blind spots that could result from using a single model. Several forecasting models and techniques have to be incorporated to form a complete forecasting system, from data collection to evaluation of uncertainties. In order to deal with uncertainty, the forecast should not rely on a single scenario, but should provide decision makers with a range of forecasts together with an indication of the probability for each.

The system forecast can be built up from its major sectors: residential, commercial and industrial. The outputs of several models for each sector have to be systematically compared, and trends in key parameters, such as market saturation rates and unit energy consumption (energy intensity), have to be examined.

Large customers that have significant electricity requirements can be analysed individually. In addition, each major industry group can be reviewed annually to determine changes in technology, finances, competitive structure, etc. Ranges of key variables can be developed in order to measure their effects on sales.

The strength of econometric modelling includes the explicit estimation of the historical response of electricity consumption to income levels and prices of electricity and competing fuels. End-use demand models can be used to analyse how much energy consumption will be required for specific end uses such as residential water heating, office lighting and industrial motors. These models can reflect how energy use is changing within sectors. While econometric models are tied to historical data, end-use models allow forecasters to incorporate expected future events such as the introduction of mandated efficiency standards or the arrival of new technologies. In conclusion, the reader is reminded that no single forecasting methodology is suitable for all situations and purposes; therefore, it is recommended to use a combination of approaches [13].

4.2.4. Historical perspective

Electricity demand forecasting has changed dramatically over the last few decades. The past evolution of forecasting methodologies has been determined by the economic circumstances. Up to the mid sixties, the economies all over the world were relatively stable and had a predictable development, which led to steady growth in electricity demand that could be forecast by using rather simple methods. The forecasting consisted mainly of examining the historical trend of demand growth and projecting the future based on the past. Underlying factors such as the price of electricity and the economic situation were not considered. This approach was adequate as long as there were no major changes in the main relationships between economic growth and consumption of energy and electricity (i.e. the intensity of energy and electricity use).

After the first oil crisis, this predictable pattern was disturbed. The world experienced economic recession and steadily rising energy prices, leading to changes in the intensity and structure of energy use. As a result of these changes, forecasting with the trend extrapolation approach was seen quickly to be no longer adequate, and analysts began to look for new forecasting techniques that would explicitly model the important changes that were taking place in energy costs and patterns of energy use. This led to the common use of econometric models that link electricity sales to several key factors in the market, such as price of electricity and competing energy forms, growth in economic activity and overall energy intensity of the economy.

After the second oil crisis, the efficiency of energy end-use became of greater interest, in particular for large energy consumers. In order to incorporate the effects of energy efficiency improvements into the forecasts, the application of models for analysing end-use energy demands became more popular. These models are capable of capturing the major underlying trends of energy uses within each sector. For example, demand forecasts in the residential sector can be based on trends in space heating, air conditioning, water heating, cooking, etc. In the commercial sector, end-use categories such as lighting, air conditioning, space heating and office equipment can be examined.

From the mid eighties, electricity consumers and suppliers started to establish closer interactions in demand and supply planning. Utility surveys of their customers became more common, and these provided suppliers with a more detailed picture of the behaviour patterns of consumers and their plans for changing energy-using appliances and equipment. Demand forecasts started to use the information collected by customer surveys as a means of estimating changes in the structure and efficiency of energy end-use.

4.2.5. Economic forecasting

Energy is a key commodity in the overall level of economic activity. As residential, commercial and industrial economic activity increases or decreases, the use of energy, including electricity, should increase or decrease, respectively. Therefore, when developing long-range forecasts of energy and electricity demand, this linkage to national and local economic development must be taken into account.

The national economic forecast provides information about the prospective growth of the national economy. This involves projections of future levels of numerous factors in the country, such as population, number and types of households, employment and production in different sectors, general inflation, wage rates and income.

Starting from the *national* economic forecast, the forecast of the local economy, i.e. in the utility's *service area*, can be prepared by using a series of econometric equations to project future levels of employment, income, industrial production and wage rates. Both national and local factors have to be incorporated into the local economic forecast. While local businesses are affected by national events, the influences at the local level are altered also by the particular characteristics of the service area. These characteristics include growth and age of population, industrial mix, and the cost of doing business locally versus nationally [14].

4.2.6. Electricity demand forecasting

The economic forecast presented in the previous section, together with a detailed analysis of the patterns of energy use in the past, provide the basis to develop the electricity demand and load forecast. Forecasts can be prepared for sales to the residential, commercial, industrial and wholesale energy sectors. In order to complete the forecast, estimates have to be made for two additional categories: utility's own use; and transmission and distribution losses.

Residential sector. There are two main factors that affect the residential sector electricity demand forecast: the number of residential customers; and the level of kWh usage per customer. The number of residential customers is affected by population in the household formation age groups and real per capita income. The income level is of particular importance in developing countries, because this can determine the number of households that are connected to the grid (in many developing countries, a significant share of the population, especially in rural areas, is not at present connected to electricity grids owing to low income levels).

The key ingredients that affect residential electricity usage are: the stock of appliances, the age and efficiency of the appliance stock, weather (which affects heating and air conditioning loads), electricity price, price of competing fuels and income. As the stock of energy-using appliances grows per customer, energy use tends to rise, although this may be offset partly by old appliances being replaced gradually with more efficient ones. The rate at which such replacement occurs tends to be price-induced, but it can be accelerated by public information campaigns and subsidies to customers [10].

Commercial sector. Commercial electricity usage changes with variations in commercial economic activity, energy prices, and the market penetration of conservation and energy efficiency improvement measures, which are driven by their costs. The forecast for the commercial sector can be prepared as a function of commercial employment, which is a measure of the sector economic activity, the price of electricity and competing energy forms, and the weather (which can influence heating and cooling loads). The stock and efficiency of selected commercial appliances (e.g. computers, copiers), can be used as additional factors in the electricity demand forecast.

Industrial sector. Since the industrial sector uses electricity primarily in production processes, it can be expected that a close relationship should exist between electricity usage and industrial production levels. The choice between energy forms for use in a process (e.g. electricity or natural gas for heating) is affected by their relative prices, while the energy intensity of the process is affected by conservation and efficiency improvement measures.

The forecast for industrial electricity sales is dependent upon local industrial production indices, the real price of electricity, the price of electricity relative to the price of other energy sources (natural gas, coal and oil), the wage rate, heating and cooling degree days, and selected qualitative variables for specific time periods (e.g. shutdowns for vacations or strikes).

Wholesale customers. Organisations that purchase bulk electric power from electricity producers, for distribution or resale to ultimate consumers, are called wholesale customers. With the widespread and growing moves towards privatisation and deregulation of the electricity supply industry, which in the past was largely monopolistic and highly integrated, wholesale customers have become a more important factor in electricity marketing. Forecasts of sales to each wholesale customer can be prepared by using the consumption patterns for the residential and/or commercial sectors. It should be noted that weather variables, or any other variable such as gas supply restrictions or marginal electricity price, could have positive or negative effects on demand.

System electricity demand. Once the forecasts for all sectors are completed, the forecast of the total system demand can be prepared. This requires that all the individual sector forecasts be combined, along with forecasts of the electricity producer's own consumption and transmission and distribution system losses. After the system demand is completed, the load forecast can be prepared as described below.

4.2.7. Load forecasting

In order to ensure reliable and economic supply of electricity under all conditions, it is necessary to forecast not only the overall level of demand (i.e. annual, monthly or weekly consumption, in kWh) but also the maximum demand (i.e. peak load, in kW) and the time distribution (monthly, daily or hourly) of the demand. Load forecasting is separated from demand forecasting because the driving forces and data requirements, and consequently the methods of forecasting, are different.

Peak load forecast. The level of peak load is affected by variations with: season of the year (e.g. heating loads in winter and air conditioning loads in summer); day of the week (e.g. higher commercial sector loads on work days than on weekends); and hour of the day (e.g. high residential sector cooking loads in morning and evening, higher air conditioning loads during the hot hours of the day). Within seasons, the peak load is affected by weather conditions (e.g. either extremely hot or cold weather can lead to higher loads), also, temperatures at times other than the peak load can be important due to the effect, for example, of heat storage in buildings.

Thus, an important step in developing the peak load forecast is the determination of the seasonal, daily and hourly variations in load caused by economic activities, and to use historical data on the typical cyclical variations in weather and temperatures in order to determine their effects on demand. The effects due to variations in economic activity can be estimated using econometric models, while other models (e.g. correlations between load and ‘degree-days’ deviation from average temperatures) have to be used to represent the weather effects.

Load shape forecasting. There is a need to forecast both sector-specific and system-wide hourly loads over the planning horizon. Additionally, the forecast methodology has to be able to analyse the effects on load shape due to a wide variety of changing conditions and utility programmes [11], including:

- conservation and load management programmes;
- rate design alternatives (e.g. time-of-day rates);
- market penetration of energy efficient technologies;
- changes in customer or end-use service mix; and
- weather conditions.

The load curve of the total system is built up from analysis of the load curves for the different energy using sectors [15]. The principle of sectoral modelling is to analyse the shape of each sector’s load curve, reflecting the behaviour of this particular sector over a given period of time. The forecasting phase consists of the aggregation of the expected sectoral development of consumption into system level figures.

Top-down models develop aggregated forecasts by sector and/or overall end-use categories. Such models do not require large amounts of input data, and therefore are well-suited to analyse socio-economic and climatic factors. However, because they do not incorporate detailed data on specific end-uses, they are not able to assess the effects of demand-side management (DSM) programmes (see Sec. 4.3).

Bottom-up models, on the other hand, build an aggregate forecast from individual components, allowing integration of the best available sector-specific or end-use-specific forecasts. These models are capable of evaluating DSM activities because they are based on detailed energy consumption data for the end-uses affected by DSM.

4.3. Demand side management (DSM)

4.3.1. The role of demand side management in the planning process

The fundamental objective of incorporating demand side management (DSM) into the planning process is the assessment of energy efficiency improvements, thus identifying the extent of benefits for the power supply system, its customers, and society in general. These benefits can be summarised as generally falling into one of the following categories:

- reduced electricity supply costs,
- societal benefits - primarily reduced environmental impacts,
- power sector competitive benefits as result of improved quality of electricity supply.

In order for the utility to adopt DSM as part of its overall business strategy, there must exist some financial interest for the power system. In other words, by implementing the DSM programmes, the power system must have the opportunity to earn profits from DSM investments, that are at least as large as the profits coming from conventional supply-side investments. However, DSM programmes are designed to reduce consumption, and therefore sales of electricity, whereas supply-side investments are made in order to increase sales. This fundamental difference has to be taken into account in the rate structures of the utility. If the actual level of electricity sales turns out to be lower (due to DSM reductions in demand) than the estimate that was used to set the electricity sales price, then the power supplier will not collect revenues sufficient to recover its costs or earn its full profit. This is referred to as 'the loss of revenues' effect of DSM. The regulatory instruments must therefore ensure that DSM programmes will not affect the power system profitability in a negative way. This requires that the power system be allowed to recover both DSM costs and the loss of revenues resulting from the programme, in order to ensure the long term financial soundness of the power system. The planning process should therefore provide for the assessment of:

- energy saving potentials of a particular DSM programme,
- costs associated with the DSM programme,
- effects on power system revenues.

4.3.2. Objective of demand side management

Customers use energy in different ways, and their consumption patterns change continually. The forecast of both level of loads and load curve shapes, at the sectoral and system levels, has to reflect those changing patterns. Demand side management has the twin objectives of load reduction and load shaping. The effects of load reduction and load shaping are illustrated in Figure 4.3. Load reduction (i.e. decreasing the overall level of demand for electricity; see Figure 4.3-a) reduces the need for investments in additional generating capacity. Flexible load shaping, e.g. through load shifting (see Figure 4.3-b, and Section 4.3.5), peak clipping (see Figure 4.3-c) and valley filling (see Figure 4.3-d), have the objective of improving the shape of the system's overall load curve (i.e. reducing the difference between minimum and peak demand). Generally, the costs of capacity to serve peak loads are high, per unit of electricity sold, since peaking capacity is used for only a small fraction of the year. Therefore, peak clipping at the time of yearly peak is one of the most effective strategies for reducing electricity costs, since it allows the utility to avoid investment in generating capacity that will be used little. Load shifting, where load is shifted from on-peak periods to off-peak periods, is another load shaping strategy which enhances the overall system load shape by distributing loads more uniformly. This strategy can reduce generation costs in two ways: by reducing the investments in peaking capacity; and by increasing the operation of mid-range and base-load plants, thereby amortising their investment costs over a larger electricity production.

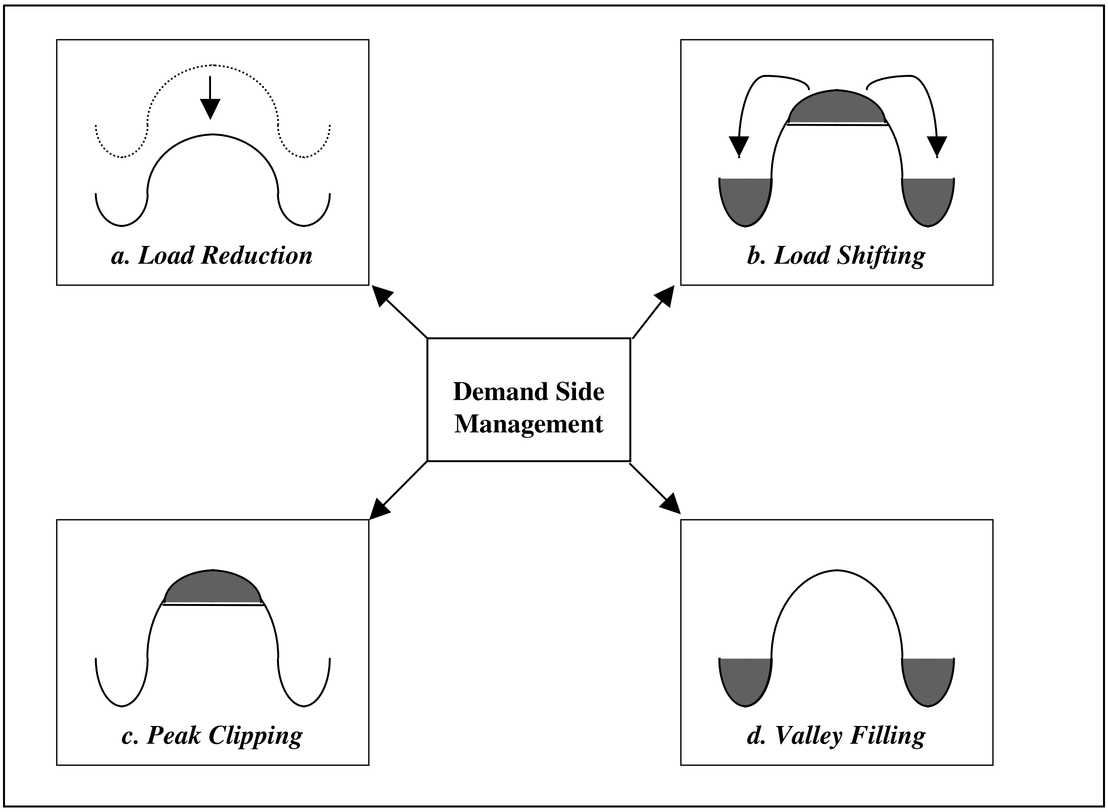


FIG. 4.3. Effects of demand side management (DSM) on the load curve.

4.3.3. Main DSM options

The term demand side management (DSM) refers to the planning, implementation and monitoring of utility activities designed to influence customer use of electricity in predictable ways that will produce desired changes (i.e. changes in the time pattern and magnitude) in the utility's loads [16]. A wide range of DSM options can be used to influence the pattern of electricity consumption, while still providing customers with appropriate levels of reliable electricity service. The applicability of specific options depends on factors such as: [17]

- Customer characteristics (e.g. types of appliances, level of consumption and use patterns),
- Utility characteristics (e.g. system demand profile, constraints on levels of fuel use and/or emissions, and demand growth rates),
- Market conditions, and
- Regulatory situation, including the allowances for DSM cost recovery.

The combination of these and other factors determines the advantages and disadvantages of DSM options in a particular country or utility. For example, in some regulatory environments, utilities are compensated for the financial risk they bear in making DSM investments and for possibly not recovering the expected full amount of fixed costs in the short term, because of sales reductions caused by DSM programmes [18].

Analysis of DSM options typically follows four steps [17]. The *design step* consists of preliminary screening, detailed economic analysis and final development of DSM measures that are deemed to be appropriate for different market sectors. The *implementation step* includes operational planning and development, pilot studies to verify technical characteristics and costs, and technology transfer (full implementation). The *monitoring step* ensures that the programme meets the criteria upon which the implementation was based. Monitoring is carried out by: observing changes induced in the system demand profile; conducting load research for large customers or groups of customers; market research to determine changes in the stock of particular appliances, such as more efficient refrigerators or lighting. The *evaluation step* has the objective of determining the benefits of DSM options in terms of economic, social, health and environmental effects. Evaluation can be a complex process that depends on the viewpoint of the evaluator, e.g. the utility, regulators, participating customers, non-participating customers or IAPs. Typically, DSM options are evaluated by comparing their estimated costs to the estimated savings, in terms of avoided costs for investment, fuel and operation or in terms of reductions in the long-run marginal cost of electricity generation.

There are a large variety of DSM options available for consideration. According to a 1994 UNIPEDE survey of 14 countries, the most frequently used DSM strategies are those shown in Table 4.1, with time-of-day rates and information campaigns being among the most popular strategies [17].

TABLE 4.1. MOST FREQUENTLY USED DSM STRATEGIES

Strategy	Number of countries
Time-of-day rates	14
Information campaigns	14
R&D	10
Seasonal rates	10
Energy audits	10
Labelling of appliances	10
Building codes	10
Interruptible rates	8
Maximum demand rates	8
Grants and rebates	8
Direct control	8
Procurement	7
Other tariffs	7

For the purposes of this section, four categories of DSM options will be described briefly: electricity tariffs; load shifting; direct demand-side investment; research and information transfer.

4.3.3.1. Electricity tariffs

The electricity tariff approach to DSM is intended to provide customers with appropriate ‘price signals’ that are designed to produce the desired outcome, e.g. purchase of more efficient end-use devices or using less electricity at times of peak load). The price signal may be given by:

- Tariffs based on long-run marginal cost of supply,
- Demand-related tariffs that account for the level of demand placed on the system (e.g. higher tariffs for customers that have high power demands),
- Seasonal tariffs that account for strong seasonal variations in loads or cost of supply (e.g. higher tariffs in seasons with low hydro power production or with high air conditioning loads),

- Time-of-day tariffs that account for the variations in cost of generation (e.g. lower tariffs at times of daily minimum demands), or
- A combination of the above.

Tariffs based on long-run marginal cost (LRMC) of supply probably are the most important component in any framework for comparing demand and supply options. LRMC is the cost of supplying an increment of demand, sustained indefinitely into the future, from a particular customer group (e.g. industrial, commercial or residential). If the tariffs for a customer group are at a level below the LRMC, the utility will not recover its full cost of providing supply, the customer will have less incentive to invest in more efficient energy-using equipment, and resources will not be used at optimal level. If the tariffs would be set above the LRMC, the customer would have a tendency to over invest in energy efficiency improvements (i.e. introduce energy savings that would not be justified by their overall economic merits), or to change to another form of energy (e.g. switching from electricity to natural gas for water heating or cooking). It is important to note that different customer groups have different levels of LRMC, because of the different costs involved in supplying each customer group. Also, basing tariffs strictly on LRMC does not ensure full cost recovery to the utility; therefore, it is customary that tariffs are adjusted to allow the utility to recover fully its costs of supply and to guarantee that the utility's financial soundness is maintained.

Setting appropriate tariffs is important, but it is not the only measure needed to encourage DSM. For example, offering lower electricity tariffs at night, when demand usually is low, will not induce consumers to shift to night usage unless facilitating technologies (e.g. heat storage systems) are available at suitable cost. Also, information programmes are important in order to inform customers about the costs and benefits of the options available to them.

4.3.3.2. Load shifting

A very important class of DSM options involves load shifting, which is different from overall load reduction through energy saving options such as more efficient light bulbs. *Direct load shifting*, or load management, occurs when the utility has the ability to switch selected customers' loads off at certain times. For example, a utility may implement supply contracts, and the technical means, allowing it to switch air conditioners off for 10 minutes during each hour. This technique effectively gives the utility a 'negative dispatch' capability. That is, rather than requesting more supply from its generating units, the utility can decrease the load from its customers, on a rotating basis. Both the utility and its customers derive benefits from the technique: the utility through reducing its cost of production; and the customer through being offered a reduced electricity tariff. From the utility viewpoint, it is important to ensure that the cost of the remote switching equipment required for implementing direct load management is offset by the savings in production costs [17].

Indirect load shifting refers to actions taken by customers in order to make best use of a particular tariff structure, e.g. time-of-day tariffs. An example would be customers who wait until times of lower tariffs to use their washing machines or to switch on water heaters or space heating equipment (this could be done, for example, by installing automatic timers). For the utility, an advantage of indirect load shifting is that it has low implementation costs, requiring only the establishment of the time-of-day tariff system; a disadvantage is the difficulty in estimating how much load shifting will be induced by the tariffs.

Figure 4.3-b illustrates the effect of load shifting on the utility's load during a typical day. As an example, water can be chilled (or heated) at night and used during the peak periods of the day for air conditioning (or heating). Thus, loads are reduced at the time of the system's normal peak load (the shaded area under the top of the curve in Figure 4.3-b), and increased at times of normal low demand (the shaded areas at the bottom of the curve in Figure 4.3-b). For some applications, such as chilling water for later use in air conditioning, load shifting involves some inefficiencies, and thereby increases the total amount of electricity used. For other applications, such as load shifting for laundry, the efficiency loss is essentially zero.

Figure 4.3-b shows that load shifting will reduce the utility's peak demand and increase the minimum demand. This results in cost savings to the utility by: reducing the need for investments in

new plants to meet the higher peak demand; decreasing the amount of generation that has to be produced by peaking units, that usually have high fuel costs; allowing the ‘base load’ plants to run at higher capacity factors, thereby amortising their investments over a larger production. The customer benefits through the lower tariffs at time of off-peak demand.

4.3.3.3. Direct demand side investment

Direct demand side investments include measures such as providing grants, rebates, low or no interest loans or tax relief to customers who purchase energy efficient equipment. Such measures may help overcome initial market acceptance problems, such as a customer being reluctant to pay a higher purchase cost even though it will be offset through lower operating cost on a lifetime basis (e.g. energy efficient light bulbs versus conventional bulbs). Rebates also encourage retailers to stock high efficiency devices and promote their sales.

4.3.3.4. Research and information transfer

Many customers have inadequate information about the availability and advantages of energy efficient equipment. Furthermore, many customers may not be aware of the different tariff structures offered by utilities to encourage load shifting.

Table 4.1 showed that all 14 countries surveyed had implemented information campaigns, ranging from information material sent together with utility bills to carrying out energy audits for customers. The campaigns may be targeted at all customers or only at specific groups of customers. Providing information can be a rapid and cost-effective measure, but it requires careful targeting and planning in order to be effective. Information campaigns are most effective when designed to motivate customers that have common needs, interests, problems and characteristics [19].

Most consumers, especially in the residential sector, are not sufficiently aware about the energy consumption of different types of end-use equipment offered in the market. This lack of information can be overcome by the use of labelling (e.g. ‘green stickers’) and efficiency performance standards. In order to be effective, equipment labelling should state the average annual energy consumption under typical operating conditions, the average annual operating costs under the local energy prices, the cost savings relative to ‘normal’ equipment and the estimated time to recover the incremental purchase cost (payback time). Efficiency standards go a step further than labelling, by defining minimum efficiency levels that have to be met by new equipment and buildings.

Research, development and demonstration (RD&D) projects can lead to the development and demonstration of new technology options that are designed to be appropriate for local conditions and can help in introducing new products or services in the market place. It is in the electricity producer-distributor’s own business interest to assist, together with public agencies and manufacturers, in improving technologies that use electricity, in order that electricity remains competitive with other energy forms [16].

4.3.4. Special data requirements of DSM programmes

When designing and implementing a DSM programme, many methodological and data problems need to be solved in order to allow supply and demand side options to be analysed and compared fairly and objectively, in terms of: capacity and energy equivalencies, measurability of resources, security of resources, dispatchability, system reliability, etc. [20].

Despite the complexity of the methodological issues, and the need to continue improving the methods applied, an overall approach had been established already in 1987 with the preparation of the so-called ‘California Standard Practice Manual’ [21]. Four basic sets of data are needed for supporting analysis of DSM options:

- electricity and energy data (e.g. tariff structures, LRMC of supplying customers);
- DSM technologies data (e.g. prices, efficiencies);
- market structure data (e.g. customer characteristics, behaviour patterns);

- market penetration data (e.g. status of development of DSM technologies, acceptance by customers, rate of sales).

Some of the required data for the electricity and energy systems may be difficult to obtain, or may contain uncertainties (e.g. costs of new generating equipment). In most cases, however, these additional difficulties are not specific to the analysis of DSM options, since similar problems existed already in classical supply-side planning. There also may be difficulties in obtaining sufficient data about DSM technologies, since some equipment manufacturers and suppliers may be reluctant, on the grounds of commercial competitiveness, to disclose adequate details about their products.

In many cases, data about the electricity market structure may be largely lacking, except where utilities have conducted market surveys. Lack of market structure data is a problem in developing countries in particular, since few (if any) surveys have been carried out in these countries.

The largest difficulties are encountered in obtaining data about the expected local market penetration of different DSM technologies, and the potential effect of different DSM measures in influencing the penetration. It can be helpful to get data from other utilities who have implemented DSM programmes and evaluated the results. However, the differences in market characteristics and consumer behaviour patterns may make data from other markets largely unrealistic in the local situation. Therefore, the conduct of ‘pilot projects’ in the local market may be the only means to obtain relevant data.

4.3.5. Regulatory environment for DSM

From the utility point of view, the fundamental change in the economic attractiveness of DSM can come when the regulatory body allows the investments in DSM to be recovered through the electricity tariffs, as is the case for investments in new supply capacity. Investing in DSM becomes a cost-effective utility business activity if: the cost of load reduction is lower than the avoided cost of supplying that amount of load; and the utility is permitted to earn a profit on the DSM investments. Regulatory changes to make the latter condition possible can provide opportunities for enhancing the efficiency and cost of electricity production and use.

DSM has been practised in a number of developed countries since more than a decade, and in some states of the USA utility regulatory commissions adopted procedures under which supply-side investments would be approved only if the utility could demonstrate that all cost-effective demand-side measures had been exploited. Some regulatory commissions also introduced procedures allowing the utility to earn profits on the DSM investments. A key move was the decoupling of the allowable profits from the ‘rate base’ (i.e. the investment value of supply-side equipment) and electricity sales level.

4.3.6. Key areas of uncertainty in DSM

DSM options have a significantly higher level of uncertainty than options on the supply-side. There are at least four key areas of uncertainty for DSM programmes. First, the estimated effect of implementing DSM measures is based on assumptions about the electricity service requirements of customers in different sectors, and about the energy consumption of existing stock of energy-using equipment. These assumptions may or may not reflect accurately the real situation.

Second, there is an uncertainty surrounding the projected acceptance levels for the proposed DSM programmes. Market surveys can be used to derive responses from customers, indicating how they likely would respond if they were offered different DSM options. However, the results from surveys have to be viewed with caution, and the actual result will be known only when the DSM option is placed on the market.

Third, there are a number of technological issues associated with DSM programmes. Post-implementation monitoring and evaluation is necessary in order to determine the relative cost-effectiveness and energy savings potential of different types of energy-using equipment. Such monitoring and evaluation may help also in identifying additional DSM options that could be applicable in the service area.

Fourth, the estimated costs for designing and implementing the DSM programme, and the cost savings to be obtained, are uncertain. To a great extent, this uncertainty can be overcome only through implementing pilot projects or full scale programmes, although useful information can be obtained by studying the experience of other utilities.

4.4. Supply side management

4.4.1. General considerations

In general, the necessity for timely and adequate electricity system planning and decision making is characterised by the following:

- Energy systems are relatively slow to change. Technology development evolves rather slowly, plant construction times can be quite long (4-5 years for coal-fired plants; 5-7 years for nuclear; and up to 10 years for large hydro power projects) and plant operating lifetimes usually are 30 years or more. Thus, the rate of equipment replacement is quite low. To a greater extent than most other sectors of the economy, planning for the electricity supply sector involves long time horizons (15 to 30 years, or even longer). This long time horizon increases the magnitude of uncertainties, and makes it difficult for the planners to obtain definitive policy guidelines from the decision makers.
- In energy and electricity planning, supply and demand are strongly interlinked, and are connected to the overall economy, requiring that analysis be carried out in an iterative or comprehensive manner. Comprehensive approaches, however, quite often face practical difficulties, owing to complexities involved in modelling the interlinkages between energy supply and demand and the connections to the global, national, regional and local economies.
- In general, the demand is for energy services (e.g. heating, cooling, lighting), rather than for energy per se. Therefore, planning for electricity supply cannot be limited to the electricity sector only, but has to take into account the competition from other forms of energy. Furthermore, the analysis has to take into account potential changes in energy demand that could be achieved through efficiency improvements on the end-use side (i.e. obtaining the same level of energy services with a lower consumption of energy) [1].

When speaking of electricity system planning, it is necessary to keep in mind that the ‘system’ comprises a number of sub-systems, namely: the fuel supply sub-system; the electricity generating sub-system (i.e. the power plants); the high-voltage transmission sub-system; and the distribution sub-system. This is a physical system whose elements are in physical interaction with each other. This interaction means that any change in the working condition of one element of the system results in changes in the working condition of other elements, and ultimately throughout the entire system.

From the discussion of DSM (Section 4.3), it is apparent that the electricity end-use equipment also forms a part of the system; however, in the traditional approach to planning, end-use has not been treated as a sub-system of the electric energy system. Today, planning tends more towards considering the end-use as an integrated part of the overall system. As a result of this conceptual change, electricity system planning is not limited to the supply side, but encompasses the demand side as well. This is a key element of the integrated approach described in this book (see Figure 4.1).

Historically, electric utilities have viewed their business as being limited to generating, transmitting and distributing electricity to its customers; that is, they were supply-side oriented. Growing demands for electricity services were met by building new power plants or increasing the amount of electricity produced at existing plants. From the utilities’ viewpoint, it was not in their business interest (i.e. selling as much electricity as possible) to work with their customers in order to meet the service needs with less electricity (e.g. through DSM measures). Although utilities still have to plan for building additional generating capacity in order to meet growing demands for electricity, they are taking a broader view of their business interest and are including DSM measures as a part of their planning.

This broader view of electricity planning helps to capture the diverse range of possibilities open to electricity supply industry today. A more workable definition of 'supply side options' is 'the actions that a power supplier can take to ensure that its customers' electricity service needs can be met reliably, while maintaining the financial soundness of the supplier'. With this broader definition, options are not limited to choices of what type of new capacity to build, but includes purchasing power from other producers, setting up joint ventures for power production, reducing losses in transmission and distribution and, most importantly, DSM measures. Utility managers now recognise that all these options offer opportunities for reducing electricity supply costs, maintaining or increasing profits, and ensuring that the utility's product (electricity) remains an economically competitive energy form for its customers [13].

4.4.2. Key issues in technology choices

4.4.2.1. Objectives of operation, operational planning and expansion planning of the electric energy system

Fundamentally, the development and operation of the electric energy system aims towards satisfying three main objectives, namely:

- Reliable and safe supply,
- Economic efficiency, and
- Health and environmental protection.

Beyond these objectives, a number of other, often contradicting, requirements may have to be met simultaneously, such as utilising domestic energy resources and industrial capabilities for manufacturing and constructing power plants.

Operation of the electric energy system involves taking the immediate decisions necessary for adapting to changes in demands for power (varying loads) and the system control, regulation and dispatching tasks associated with this (e.g. plant start-ups and shut-downs; electrical frequency control). Owing to the immediacy of the decisions that have to be taken, the operation functions are performed essentially in an on-line mode (i.e. in 'real time'). Operational and expansion planning, on the other hand, are for the purpose of developing plans for meeting expected future demands in the short term (operational planning) and medium to long term (expansion planning), and are performed mainly in an off-line mode (i.e. analysing possible strategies for meeting various possible future levels of demand).

Operational planning has the objective of preparing short term plans (i.e. from the next few hours to the next few months) for system operation, taking into account expected demands, availability of plants, seasonal variations in capacities of plants (e.g. due to cooling water temperatures for thermal plants or reservoir levels and allowable or optimal water discharge rates for hydro power plants). A particular feature of electric system operational planning is that it focuses on how to meet demands best with the existing technical equipment (plant types, capacities and locations; fuel availability and cost; transmission and distribution line capacities; etc.), since the planning horizon is too short to consider adding new equipment to the system.

Expansion planning (system development planning) has the objective of determining medium to long term (in the order of 10 to 20 years) strategic plans for adding new technical equipment to the existing system, in order that the system's electricity supply capabilities will keep pace with the expected growth in customers' demand. Thus, the main focus of expansion planning is on the available options for new equipment. Nonetheless, in the planning for new equipment additions, the existing system has to be taken into account since it will have an effect on, and will be affected by, decisions about what types of new generating units should be added to the system.

Expansion planning is a very complex task, which generally requires that the problem be decomposed into several parts, each of which can be solved only with sophisticated computer models (e.g. the IAEA's WASP model [22]). Various expansion planning modelling approaches that can be used for the different parts of the overall planning task are reviewed in Section 4.4.4.

The optimisation models employed for operational and expansion planning of electric energy systems utilise an objective function that aims towards minimising the total cost over the planning horizon, while ensuring that reliability, safety, health and environmental requirements are met also. Usually, these additional requirements are treated as constraints (e.g. total sulphur dioxide emissions from the cost-optimised generating system must not exceed a specified limiting value). However, when it is possible to establish monetary values for any of these aspects (e.g. estimated value of damage caused by emission of sulphur dioxide, in $/tonne emitted), the value can be 'internalised' and taken into account within the cost optimisation.

The optimisation calculations always define the minimum cost expansion programme. However, the resulting 'optimum' plan is actually a 'constrained optimum'; that is, it is the lowest cost plan that meets all of the constraints that have been imposed. A different optimum plan might be found if different constraints were to be imposed. Therefore, it is important to keep in mind that no 'minimum cost' plan exists, in an absolute sense, since the model does not have complete freedom owing to the constraints. In order to test the sensitivity of the optimum plan to the constraints imposed, the optimisation should be carried out with a range of values for the constraints. Such sensitivity studies can provide valuable additional information about the cost to the system of different values for the constraints (e.g. the additional cost to the electricity system if, for example, there were to be a 20% reduction in the limit on allowable sulphur dioxide emissions).

4.4.2.2. Technical constraints taken into account

The special technical features of the electricity supply system have to be taken into consideration in the course of the system expansion planning task [23]. Since no single technology is suitable for all purposes, it is necessary to have a balanced mix of energy sources and generating technologies. For a given utility, region or country, the optimal mix depends on a complex set of technical factors, some of which are discussed below.

System load profile. The system load level and load profile (see Section 4.2.7) are important determinants of the technologies that are suited best for adding to the system. Changes in the load profile (e.g. through DSM measures) will lead to changes in the capacity shares of base-load, load-following and peak-load plants in the optimised generation mix.

Technical features of power plants. Most types of power plants have certain technical constraints on how they are operated. For example, there usually is a lower capacity limit at which a generating unit can be operated safely. In other words, if the cost minimisation would require a plant to operate below its lower capacity limit, then this plant would have to be shut down completely and substituted by another plant, even though this would lead to higher costs. Also, each type of power plant has a limit on the rate at which the power output can be changed, and this has to be taken into account, in particular in operational planning, in order to anticipate changes in demand. Furthermore, a comprehensive periodic maintenance programme is important in ensuring safe and reliable operation of power plants. Nuclear power plants have an additional requirement for periodic shut-downs in order to carry out refuelling operations and safety inspections. The frequency and duration of the periodic *scheduled shut-downs* for maintenance, refuelling and inspections have to be taken into account in determining the availability factor (i.e. the fraction of time that the unit will be available for generation, if it should be needed). Finally, all power plants experience *unscheduled shut-downs*, owing to failures of components. The frequency and duration of unscheduled outages generally are derived from operating experience records for similar plants.

Supply reliability and quality. Electricity supply and demand have to be kept continually in balance, since there is no economically viable technology for storing large quantities of electricity. To a great extent, this applies also for the heat supplied by cogeneration plants. The reliability and quality of an electricity supply system are characterised by its Loss of Load Probability (LOLP) and degree of constant electrical frequency. Taking into account the possibility of forced outages, ensuring a low LOLP and a constant electrical frequency requires that the available generating capacity is always greater than the customer demand. The difference between available capacity and demand is called ‘reserve margin’. Some part of the capacity in the reserve margin has to be provided by plants that are on line, but operating at zero or partial power, in order to be able to respond to sudden changes in load or to take over in the event that another plant suffers a forced outage. This part of the reserve margin is called ‘spinning reserve’, meaning that the capacity is in reserve but with the turbine-generators spinning. This function is served well by open-cycle gas turbine units and by hydro power plants with water storage reservoirs, both of which are quick starting and capable of rapid changes in power level.

Both the overall reserve margin and the spinning reserve margin have to be taken into account in the operational and expansion planning for an electricity supply system. Clearly, there are trade-offs between maximising system reliability and quality and minimising system costs.

Lead time for plant implementation. In expansion planning, the lead time required for plant implementation – including site selection, licensing, bidding, construction and start-up testing – imposes a constraint on the earliest date at which a plant can be made available to meet new capacity needs. The construction lead time varies from about two years for an open cycle combustion turbine unit, four to six years for coal-fired units to five to seven years for large nuclear and hydro power units. The site selection, licensing and bidding process can require as little as a year for open cycle combustion turbine units to as much as five to six years (or even more) for large nuclear and hydro power units. Clearly, units having shorter implementation lead times provide the utility with greater flexibility in responding to unexpected changes in rates of demand growth.

Fuel utilisation constraints. In some countries, there may be government policies aiming towards protecting the domestic fuel production industries or limiting the national dependence on imported fuels. These policies can lead to constraints on the utilisation of certain fuel types, for example by requiring that utilisation of a certain fuel type has to be: above a lower limit (e.g. a specified minimum amount of domestic coal must be used); or, below an upper limit (e.g. on the amount of coal that can be imported); or, maintained between lower and upper limits. Such constraints will have an effect on the dispatching of power plants that burn those fuels and, in some cases, may require that a certain type of power plant be chosen (alternatively, that it not be chosen) for meeting new capacity requirements.

4.4.2.3. Other influencing factors

There is a wide range of generation technologies that are, in principle, available to be used for generating electricity from fossil, nuclear and renewable energy sources. However, these technologies have to be deployed in a complex, competitive market place of national electricity enterprises, regulated private utilities and independent power producers. Meeting these demanding and dynamic market conditions requires a wide variety of technology options that can be implemented on a timely schedule that matches demand growth trends, load requirements and investment capabilities. Generating technologies also have to meet the established regulatory requirements, such as pollutant emission limits and safety standards. The following section discusses some of the factors that can have positive or negative influences on the choice of electricity generating technologies [4, 5].

Security of fuel supply. The security of fuel supply, as well as the stability of fuel prices, can be enhanced through diversification of the types of fuels consumed and the sources of their supply. Security of fuel supply is of particular importance for energy importing countries, for example to guard against supply interruptions such as those experienced during the oil crises during the 1970s. Therefore, utilities generally plan for a balanced mix of energy sources in their generation systems. Such a mix makes it possible for the utility to switch among fuel types and sources of supply in the event that one type or source experiences a price increase or shortage of supply. For example, the demands on natural gas for the domestic sector usually are higher in winter, and the utility may find it necessary to switch from power plants burning gas to those burning coal. In the planning process, it is necessary to take into consideration the need to provide capabilities for fuel switching, for example by installing power plants that can burn more than one type of fuel (coal/oil; oil/gas; etc.).

Providing adequate capacity for fuel storage also can be very important from the point of view of enhancing security of supply and stability of price, by allowing the utility to ‘ride out’ short term price increases or to take advantage of price decreases. The additional costs of providing large storage capacities have to be taken into account during the planning process, and the risks of accidents in fuel storage have to be evaluated.

Economic and financial constraints. The ‘optimum’ generation system expansion plan is feasible for implementation only if it also meets the utility’s criteria of financial soundness. That is, developing a plan that achieves minimum long term generation costs is a necessary but not sufficient condition. In order to be feasible, the utility must be able to finance the necessary capital investments and operating costs of the expansion plan, without being exposed to ‘imprudent’ financial risks. Therefore, the optimum expansion plan that is developed through cost optimisation techniques has to be subjected to further analysis in order to determine the impacts that implementation of the plan would have on the utility’s financial balance sheet.

Environmental protection requirements. Regulations relating to plant safety and protection of human health and the environment are strengthened regularly, especially in developed countries, as new scientific information becomes available on the risks of potential accidents or the damaging effects of pollutants. In some cases, environmental protection regulations do not specify emission limits for individual facilities, but are based instead on the so-called ‘bubble-principle’, which specifies emission limits for the total generating system. Following the revision of regulations, new power plants are required to meet the new regulations in order to be granted an operating license.

When the competent regulatory body or national legislative body is considering the strengthening of environmental protection regulations, careful consideration has to be given to the question of how existing plants will be affected by the new regulations. Existing plants sometimes are exempted from meeting new regulations, through a so-called ‘grandfather clause’, or may be required to upgrade to the new standards over a specified period of time. Strict application of tighter emission limits may require the shutdown, or the limiting of operation, of existing units, which can lead to shortages of power supply or decreases in quality of supply. As a consequence, the planned schedule of power station construction may have to be accelerated, possibly with significant cost and financial implications to the utility. In summary, environmental protection requirements relating to the existing power system should be determined on the basis of a rational investigation of benefits and costs.

Regulatory and institutional constraints. Licensing requirements and the processes for approving the construction and operation of generating plants are highly dependent on the type of plant and on site specific factors. In many countries, there is a complicated regulatory approval process that involves a sequence of actions by a variety of government agencies and that provides opportunities for considering the views of IAPs. The completion of these actions can lengthen considerably the overall lead time for project implementation. However, failure in properly co-ordinating and executing the various actions, and in particular failure to consider the views of IAPs, may lead to long construction delays, cost over-runs or even cancellation of the project.

Electricity tariff regulations can determine the allowable rate of return on power plant investments, or the profit margin of the utility. In many countries, the trend towards deregulation and privatization of the electricity sector could lead to the need for higher rates of return on investments, since private industries generally seek higher returns (and shorter payback times) than do public utilities.

Recent regulatory changes in a number of countries are designed to enhance market competition in the electric sector by requiring utilities to allow independent power producers the opportunity to supply new capacity and electricity needs. Such changes in the utility business are leading to changes in planning approaches also [4, 5].

Consensus building and public acceptance. The issues related to electricity production and use involve fundamental decisions that affect, directly or indirectly, all aspects of society. Owing to the far reaching implications of decisions taken in the power sector, there is a trend towards increasing involvement of IAPs in the decision making process. As a consequence of this trend, it has become increasingly important to build a consensus among all IAPs, and to develop public acceptance, in support of power sector decisions. The consensus building process can be enhanced greatly by comparative assessment studies of alternative generation technologies, fuel mixes and expansion strategies. The data bases and analytical softwares developed within the IAEA's DECADES project are designed to assist in making such comparative assessment studies [24], which provide objective information on the comparative costs, safety risks, health effects and environmental impacts of different technologies and alternative expansion strategies. When made available to decision makers and IAPs, and disseminated through public information programmes, this information can assist in reaching a consensus on the most acceptable, near least cost, expansion strategy.

4.4.2.4. *Interconnection agreements with other utilities*

Electric utilities in neighbouring regions or countries usually have interconnected electricity transmission networks. These interconnections allow electricity to be interchanged between utilities, thereby providing each utility with opportunities to increase the reliability and quality, and to reduce the costs, of electricity supply. The contracts and agreements governing interconnections typically relate to the following functions:

- Furnishing mutual emergency assistance and providing backup power supplies (e.g. in the event of unexpected power plant outages), within the capabilities of the assisting utility to continue to meet its own load requirements;
- Permitting sales and purchases of electrical energy among the interconnected utilities, for the purpose of reducing overall costs to all parties or to meet short term capacity deficiencies of one of the parties;
- Permitting the exchange of power and energy during periods of planned maintenance outages of generation and transmission facilities belonging to one of the parties;
- Permitting the transfer of electric energy from one party, through the transmission system of a second party, for the benefit of a third party.

The tariffs applicable to the above classes of power and energy interchange can be set forth in appropriate rate schedules [14].

4.4.3. *Main technology options*

The following sections provide a brief overview of the main fuel sources and technology options for electricity generation. Additional information is provided in Annex II, and detailed numerical data, as well as technical, economic and environmental characteristics, on different energy chains and technologies can be found in the technology data bases established by the IAEA in the context of the DECADES project [24].

4.4.3.1. *Fossil fuelled chains*

Worldwide, coal reserves are very large, and are assessed to be adequate to meet almost any projected level of consumption for periods measured in centuries. For many countries, coal is an abundant, familiar and relatively inexpensive fuel for electricity generation. Given its large base of natural resources and established conversion technologies, coal is expected to retain its present large share in electricity generation. A major challenge, therefore, is to develop and promote deployment of techniques for using coal more efficiently and with reduced environmental impacts ('clean coal' and 'advanced coal' technologies). In this regard, fluidised bed combustion technologies are viewed as having good prospects for both new plants and for 'repowering' of existing pulverised coal burning plants. This technology is attractive in particular because it may allow coal burning plants to comply with regulatory limits on emissions of sulphur dioxide and nitrogen oxides, without the need to install flue gas desulphurisation (FGD) equipment.

Crude oil reserves are much smaller than those of coal. Known reserves are assessed to be adequate to support present consumption rates for only a few decades. Also, the need to ensure adequate supplies of oil for essential and non-replaceable uses, such as in the transportation and household sectors, as well as the experiences with the oil crises during the 1970s, have led to policies aiming towards reducing the use of oil for electricity generation. As a consequence, in many countries oil is not considered a viable fuel option for electricity generation in the long term, with the possible exception of peak-load plants.

Natural gas reserves are similar in magnitude to those of oil (i.e. much smaller than reserves of coal). Therefore, although natural gas reserves will be able to sustain present consumption rates for several decades, large scale switching from coal to natural gas for electricity generation may be difficult to sustain in the long term. In response to increasing demands for natural gas, the price of gas is likely to rise relative to that of coal. Gas prices often are connected to oil prices, in terms of equivalent energy content, owing to the fact that the two fuels are interchangeable for many applications. Natural gas combustion has relatively low emissions of carbon dioxide (a greenhouse gas of major concern because of the potential risk of global warming) and other atmospheric pollutants, and produces no solid wastes. However, adequate measures must be taken to guard against leakage of methane (itself a greenhouse gas) during production, transportation and use. With regard to power generation technologies that burn natural gas, it is expected that during the next decades significant advances will be made in open cycle combustion turbine and combined cycle power plants. Progress in gas-turbine power generation technologies will be assisted by ongoing research and development efforts aiming towards improving fuel efficiency and power levels of both commercial and military aircraft engines.

The future shares of fossil fuels in the energy mix for electricity generation will be determined largely by the success of R&D programmes directed towards reducing the cost and increasing the efficiency of fossil fired power plants, and by the effects of national and international commitments that may be adopted aiming towards mitigating the emissions of carbon dioxide and other greenhouse gases.

4.4.3.2. Nuclear power

Nuclear power has the economic, technical and fuel resource potential to make a large contribution towards reducing atmospheric pollutant emissions from electricity generation. In 1996, some 17% of the world’s total electricity production (around 7% of primary energy use) was provided by nuclear energy. Known resources of nuclear fuels (uranium and thorium) are sufficient to sustain an even larger utilisation for many decades. Various options, including spent fuel reprocessing and plutonium recycling as well as other advanced fuel cycles, are being developed and have the potential to expand even further the nuclear power capacity that could be supported by the known, conventional nuclear fuel resources. In the longer term, breeder reactors would allow nuclear energy to provide an essentially inexhaustible energy supply.

The continued evolution and improvement of reactor designs, emphasising standardisation, short construction time and passive safety features, could help to alleviate real and perceived concerns about the safety and economic risk of nuclear power, which presently exert a constraining influence on nuclear power expansion.

4.4.3.3. Hydropower

Hydropower, the main contributor of renewable energies to electricity production, produces about 19% of the world’s total electricity. Although the resource availability of hydro energy is finite, untapped resources still exist, especially in developing countries. However, exploitation of hydroelectric power is not expected to undergo large expansion at the global level during the coming decades, partly because of concerns about the social and environmental impacts of large hydro projects, and partly because of difficulties in meeting the large investment requirements [6].

4.4.3.4. Other renewable energy sources

Other than hydropower, the share of renewable energy sources in electricity generation is less than 1% today. Substantial research and development efforts are being made aiming towards enhancing the technical and economic performance of solar, wind, biomass and other renewable energy technologies. Already, some of these technologies are economically viable in favourable locations (e.g. wind power in locations with steady strong winds; solar power in remote locations not connected to electricity distribution networks). However, most experts do not expect that renewable energies will provide more than some 1-2% of the world's electricity by the end of the next two decades.

Renewable energy sources for electricity generation have to meet criteria similar to those applied to 'conventional' energy sources (e.g. fossil fuels, hydropower, nuclear energy):

- the energy source should have an adequate resource base, that can be produced in quantities suitable for power generation purposes. For renewable energy sources like solar, wind and geothermal, this implies that the natural energy (which is, by definition, inexhaustible) can be collected in adequate quantities and converted to electricity with a practical efficiency;
- electricity generation utilising the energy source must be economically competitive with alternative options;
- safety risks and social and environmental impacts must be acceptable and should not be higher than with competing fuels.

With regard to electricity generation system expansion planning, special consideration has to be given to the stochastic availability of renewable energies; that is, the intensity of wind and sunshine varies with the time of day and the season of the year, and these variations cannot be forecast with certainty (e.g. solar power electricity generation is influenced strongly by periods of cloudiness, rain, etc.). Therefore, the introduction of a large share of generation based on renewable energies can lead to a higher uncertainty on the reliability of supply being available when it is needed.

4.4.3.5. Cogeneration

A cogeneration plant is a dual output thermal unit that produces both electricity and useful heat output (steam or hot air). There are two versions of cogeneration plants. In a 'topping cycle' plant, high-pressure steam from the boiler is passed first through a high-pressure turbine to generate electricity. The low-pressure steam from the exhaust of the turbine is passed to some industrial facility, where it provides low-temperature process heat, or it can be used as the heat source for municipal district heating systems. In a 'bottoming cycle' cogeneration plant, the high-temperature steam is first used in some industrial process that requires high-temperature process heat. The exhaust heat from the industrial process is then recovered in a 'waste heat boiler', which produces low-pressure steam that is used to generate electricity. Combined-cycle (a gas turbine coupled with a steam turbine) cogeneration plants provide a very efficient energy conversion system.

Owing to the cost of building heat distribution networks for district heating, existing district heating systems offer the best opportunities for introduction of cogeneration plants. Many existing systems utilise heat-only power plants, that could be upgraded to cogeneration systems, with the heat distribution system continuing to be used, thereby reducing costs relative to a completely new cogeneration and district heating system.

4.4.3.6. Non-utility generation

Non-utility generation refers to electrical generation by facilities that are owned and operated by electricity producers other than a traditional utility. Non-utility generators (NUGs) include private and municipal utilities, large electricity using industries with their own power plants, and independent power producers. Electricity production that is surplus to the NUG's own needs usually is sold to the local utility for distribution to its customers.

Non-utility generation which supplies electricity to meet the producer's own needs, or is sold directly to a customer other than the utility, is referred to as 'load-displacement' generation, because such generation displaces load which the local utility otherwise would have been responsible for supplying.

4.4.4. Planning approaches

The growing complexity of power system expansion planning, and the increasing amount of input data required, caused the development of a number of different methodologies to carry out the necessary calculations. These methodologies utilise different mathematical approaches for electricity production simulation and for cost optimisation, which are the two main complementary tasks. The different methodologies have advantages and disadvantages depending on: the nature of the planning task; data availability; the time available for the planning task; and the manpower and computer resources available to carry out the calculations.

Power system expansion planning methodologies are designed to find the least cost plan for generation system expansion over a medium to long term planning horizon, usually some 15 to 30 years. The methodologies operate by: first, determining various feasible installation schedules (expansion paths) of new generating plants that will meet the projected electricity demands; second, using electricity production simulation to evaluate the cost of electricity generation for all feasible expansion paths; and finally, comparing the costs of different expansion paths in order to find the least cost path. The two major functions of power system expansion planning methodologies are therefore electricity production simulation and cost optimisation. Generation systems dominated by hydropower plants have different technical features compared to systems based mainly on thermal power plants (fossil or nuclear), and hence different planning approaches are used for hydro dominated systems [1].

4.4.4.1. Production simulation

The purpose of electricity production simulation is to simulate the operation of generating units, and to calculate: the amount of energy generated by each unit; the production cost of each unit and of the entire system; and the reliability of the electricity supply from the system. Both the simulation of operation and the additional calculations take into consideration the frequency and duration of planned outages (e.g. for maintenance and/or refuelling) and probabilities of forced outages of generating units. The two basic approaches to production simulation are: the Monte Carlo method; and the probabilistic simulation method.

Monte Carlo method. With the Monte Carlo method, the simulation of system operation proceeds in chronological order. For purposes of illustration, assume that the simulation is carried out with one hour time intervals. In order to determine which generating units are on forced outage, a random number is drawn for each generating unit for each one hour period during the simulation horizon. If the random number drawn is less than the forced outage probability of the unit under consideration, then that unit is on forced outage during that hour. When the probability distribution of forced outage duration is known also, both the time of occurrence and duration of forced outage may be decided by random numbers. Once it is determined which generating units are on forced outage, the production simulation for that hour becomes deterministic. The chronological order of simulation makes it possible to consider: (a) start-up of cycling units, (b) an accurate simulation of pumped storage units, (c) unit commitment rule, (d) spinning reserve, (e) effect of electrical transmission inter-ties. The disadvantage of this approach is that the results obtained from a number of runs are always slightly different, even with the same input data, because of the use of random numbers in the model. However, a reasonably converged 'average' solution can be obtained by running the simulation a number of times with the same input data.

Probabilistic simulation. With the probabilistic simulation method, the chronological sequence (e.g. hour by hour) of loads during a period (e.g. one week or one month) is arranged in decreasing order from maximum to minimum load during the period, thereby creating a 'load duration curve', or a 'load probability function'. The load probability function represents the probability that the load will equal or exceed a given value during the period. The energy generated by a generating unit during the period can be calculated by integrating over the load probability function corresponding to that period and the time length of the period. The main advantage of the probabilistic simulation approach is that the load distribution over a long period (such as a month, a quarter-year, or even a year) can be handled in a single load probability function. Thus, the method is more suitable for large generation systems for which many repetitive calculations must be performed, and it avoids the variance of results which is characteristic of the Monte Carlo method.

4.4.4.2. Approaches for capacity expansion optimisation

In capacity expansion optimisation, decisions must be made on the type, size and timing of generation unit additions during the planning period. The goal is to install capacity on an economic basis while maintaining system reliability. The type and size decisions depend on how the new units are to be operated among the existing generating units. Capacity expansion optimisation models use different mathematical optimisation methodologies, such as dynamic programming, year-to-year optimisation, linear programming, non-linear programming, mixed linear-integer programming, etc.

Dynamic programming. The dynamic programming algorithm, which is useful for making a sequence of inter-related decisions, is a systematic procedure for determining the combination of decisions that optimises the desired outcome within the bounds of constraints. In each year of the study, the procedure considers several numerical combinations of the available alternative resources. Each unique combination of these resources is considered as a 'state'. The primary objective is to minimise the selected objective function (e.g. least cost) subject to specified constraints (e.g. system reliability). The procedure starts with a fixed initial condition (state), and finds the optimum expansion plan to reach each of the states (generating mix) that are feasible for the final year (planning horizon) of the study (in this illustrative description, it is assumed that the planning horizon is divided into one year periods; however, other period lengths could be used). This approach determines, for each year and for each feasible state (generating mix) in that year, the optimum expansion path from the previous year. The user must be aware of a few characteristic aspects of dynamic programming optimisation when applied to capacity expansion optimisation. First, constraints may be used in order to limit the number of expansion alternatives to be evaluated in each period. Second, as the study horizon increases, the total number of feasible states for each period grows rapidly, leading to a substantial increase in computing requirements. Third, the calculations can be extended beyond the actual horizon of interest in the study, in order to reduce the tendency of the cost optimisation to select less capital intensive generating units toward the end of the study horizon.

Year-to-year optimisation. In this approach, the expansion decision is made by optimising only for one year at a time, without referring to information about the future. Although the computing requirements for this approach are much smaller than those required for a global optimisation, the approach tends to introduce generating units that are less capital intensive, since those are lower cost for the given year, which may lead to a sub-optimum solution over the longer term planning horizon. Moreover, as this approach does not, by definition, 'see' the future, it can lead to unrealistic solutions in situations where rapid changes occur in the system. For example, the year-to-year approach would anticipate a situation where the demand begins to increase rapidly, and would not build capacity in advance in order to meet the larger demand growth, as would be possible in approaches that incorporate a 'foresight' capability. As a second example, the year-to-year approach would not be able to foresee a situation where a given limited energy resource is nearing exhaustion, and therefore would not anticipate the need to make a timely switch to another more abundant resource.

Linear, non-linear, mixed linear-integer programming. There have been numerous applications of linear programming to optimising both electric generation operation and capacity expansion, taking into consideration certain constraints (e.g. emission constraint, fuel availability, etc.). Many of these applications have been successful. However, the use of linear programming, in place of probabilistic simulation and dynamic programming, for long range capacity expansion planning remains a formidable challenge because: (a) all the dependent variables should be expressed or approximated by linear functions, which may not represent realistically the real nature of the variables; (b) incorporating the probabilistic nature of forced outage into linear optimisation is difficult; (c) the capacity of a generating unit determined by linear programming is a continuous function and must therefore be rounded to the nearest multiple of the capacity of the candidate unit. The discrete nature of generating units can be treated by mixed linear-integer programming but, as the number of integer variables increases, there is a severe increase in the computational requirements.

Non-linear programming allows non-linear dependent variables, but its application is limited to special cases.

4.4.4.3. Planning the expansion of predominantly hydro systems

Electric power generation systems with a large hydro component (i.e. predominantly hydro systems - PHS) have specific technical characteristics that should be accounted for properly in their modelling for expansion studies, as follows: (i) random availability of the 'fuel' i.e. water and (ii) time coupling of operation decisions (today's optimal dispatch policies depend on the present and the future configuration of the power system). This is particularly important when large reservoirs with multi-period water storage capability exist or are candidates for expansion. Another characteristic that has to be taken into consideration is the possibility that significant volumes of water, that otherwise could be used for electricity generation, will be needed for non-energy uses (e.g. for irrigation or potable water for cities).

Furthermore, the value of water in the reservoirs depends on future electricity demands and future thermal generation capacity and costs. This means that, in order to determine the most economic use of hydropower resources, it is necessary to know the complete optimal expansion plan. It is not possible, therefore, to decouple the economic dispatch planning of the hydroelectric resources from the least cost expansion planning of the entire generation system.

When assessing the reliability of mainly hydro systems, uncertainties related to water availability are, in most cases, more important than those related to the forced outages of thermal generating units. Reliability problems with hydropower units usually translate into inability to provide sufficient electrical energy on a sustained basis, rather than inability to serve the peak load. If consideration is given only to the available hydro power *capacity*, the wrong impression might be reached that the hydro system has adequate reliability, whereas the system might actually not be able to provide the *energy* needed during the period under consideration. Thus, it has to be kept in mind that the use of planning methods that fail to provide proper modelling of the hydro resource uncertainty and the dynamics of optimal operation policies for hydro systems are likely to lead to erroneous results.

Some modern computer systems for expansion studies of PHS (e.g. SUPER [25]), utilise a decomposition strategy that is based on a mathematical optimisation technique called Benders decomposition [26]. In this procedure, a co-ordinator module determines, based on an approximate dispatching scheme for all of the generating units, feasible capacity additions (expansion paths) that will meet the projected electricity demand. These expansion paths are passed to an operation module which determines the optimal dispatching scheme for each path and, in the process, calculates the marginal value of each expansion candidate (Benders cuts). This dispatching scheme and marginal value information are fed back to the co-ordinator module, which derives revised optimal expansion paths. The iteration between the two modules continues until the expansion plan derived by the co-ordinator module and the dispatching scheme derived by the operation module reach agreement, within an acceptable margin of difference. The iterative process is illustrated in Figure 4.4.

Hydro-thermal dispatch. A typical hydro-thermal dispatch model simulates the optimal (least cost) operation of a generating system that contains significant capacity in both hydro and thermal power plants, taking into account uncertainties on the hydro energy resources. Hydro subsystems are assumed to be interconnected by capacity balanced transmission lines having specified loss factors equivalent, thereby leading to the definition of an 'equivalent reservoir'. The solution algorithm is based on a mathematical optimisation technique known as 'stochastic dynamic programming', that can be summarised as follows:

- The optimal dispatch of each interconnected region is first determined using stochastic dynamic programming with two state variables: energy content of the equivalent reservoir of each region [25]; and hydrology tendency, as quantified by the total (in energy) natural hydro inflow of the previous period (month).

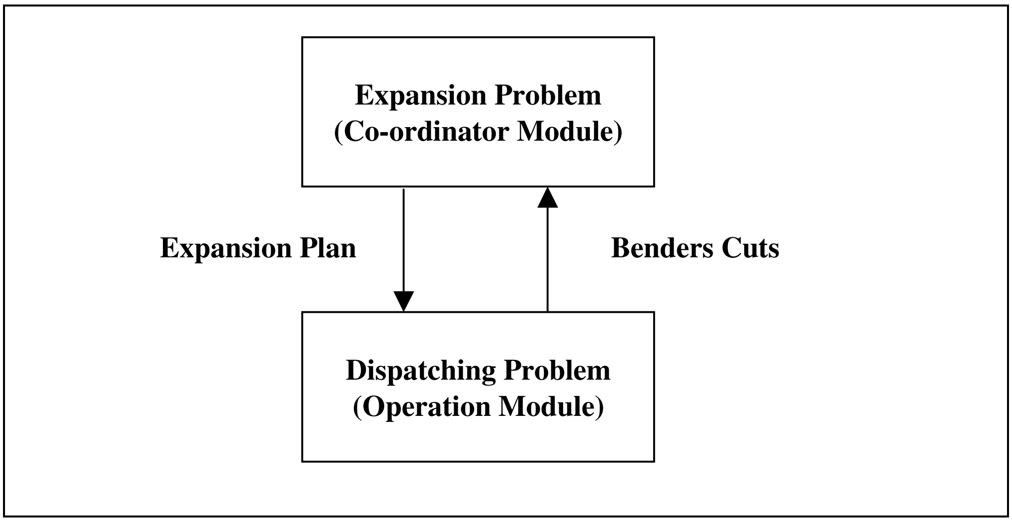


FIG. 4.4. Iterative process for obtaining least-cost expansion plans in PHS.

- Optimal interchanges are then calculated by proceeding from regions with lower to regions with higher marginal values of water (that is, the economic value of having an additional unit of water in the reservoir) for each period modelled, taking care to not exceed the energy carrying capacities of the interconnection lines. The demand of each region is increased (decreased) to account for its exports (imports) of electricity, as determined by the optimal interchange calculation.
- Iterations are performed as needed, until the total dispatch cost does not change beyond a given tolerance from one iteration to the next.
- A simulation phase follows that uses either historical or synthetic inflows and calculates useful statistics, including hour-of-day marginal costs and marginal benefits (operation gradients) of thermal projects and of interconnection lines, which provide information that can be used to adjust the expansion plan. Energy and capacity reliability indicators are provided also, which allow to assess the adequateness of the expansion plan.

The marginal costs mentioned above are useful in setting tariffs and in assessing the adequateness of an expansion plan. If marginal costs are very small, it might be an indication that the system has higher than optimal reserve capacity. On the other hand, if marginal costs are very high, it would indicate that the reserve capacity is too low.

Marginal benefits of interconnection lines are defined as the reduction in system cost what would be achieved by increasing interconnection lines by one unit of load carrying capacity. Marginal benefits (operation gradients) of thermal projects correspond to the reduction in the system cost that would be obtained by increasing that class of thermal plants by one unit of generating capacity. Marginal benefits that are higher than the annualised unit energy costs for a given year might indicate that it would be desirable to install an interconnection line or a thermal plant in that particular year. Both marginal costs and marginal benefits, therefore, are useful in adjusting a given expansion plan in order to reach an overall optimum plan.

Obtaining least-cost plans. As explained above, the problem of obtaining a least cost plan can be divided into two stages: investment planning and dispatch planning. In the first stage (investment planning) a decision is made on an expansion plan, whose operation is simulated in the second stage (dispatch planning), which provides feedback to the first stage. Based on this feedback, the expansion plan is reoptimised and the process proceeds iteratively until the two plans reach agreement, within a specified margin of difference.

Mathematically, the problem of obtaining a least cost plan can be set up as a problem of minimising the sum of investment cost plus operation cost plus value of load not served (energy rationing cost), subject to operation and investment constraints. The objective function and the constraints can, in some cases, be treated as linear variables. However, some cannot be linearised; for example, the installation of a new generating unit is formulated as a binary variable (zero-one: where one means installation, and zero means no installation).

The problem so formulated is a large scale, integer linear programming problem, that can be solved with special purpose algorithms based, for example, on Benders decomposition which was illustrated in Figure 4.4.

The operation sub-problem obtains, in addition to the optimum dispatching scheme, an indication of how the expansion plan should be adjusted, in the form of a 'Benders cut'. This is the vector of dual variables of the optimal solution to the operation sub-problem, and is made up of the marginal benefits of projects that are candidates to be incorporated in the expansion plan.

4.5. Environmental impact assessment

4.5.1. The concept of environmental impact assessment

All technologies and fuel cycles used for generating electricity have environmental and social consequences that need to be taken into account in the comparative assessment of different electricity options and strategies. There are impacts at each stage of the energy chain, including: fuel extraction, preparation, transportation, conversion to electricity, waste processing and waste disposal. Low probability but high consequence accidents - such as oil and gas fires, hydropower dam collapses, oil tanker and coal mining accidents, and nuclear facility accidents leading to the release of radioactive materials - can injure people and cause deaths. The more routine 'industrial accidents' - such as deaths and injuries among workers during the construction of facilities or vehicle wrecks during the truck transportation of fuels - often are overlooked, even though the cumulative impacts from routine accidents usually are larger than those from low probability accidents. In addition, the construction and operation of large facilities can cause nuisances through excess noise and visual intrusion. Releases of noxious substances to the atmosphere, into waterways or onto land can harm human health and damage buildings and crops.

Industrial developments must comply with a wide range of planning and environmental regulations which are evolving continually. It is the responsibility of developers to ensure that their developments comply with these legal requirements. Environmental impact assessment (EIA) is only one of several factors affecting the strategic direction of development of the overall power system and decisions on the siting of individual power projects. Economic assessment of alternatives remains the most important factor from the planner's point of view, but strategic EIA is needed in order to ensure that capital expenditure decisions made today are sufficiently resilient to be adaptable to possible future changes in environmental standards and regulations. The health and environmental dimensions of electricity generation in relation to decision making were reviewed comprehensively during the joint inter-agency Senior Expert Symposium on Electricity and the Environment (Helsinki, Finland, 1991) [4] and the International Symposium on Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making (Vienna, Austria, 1995) [5]. EIA at the sectoral and project level is the primary means for ensuring that environmental factors are fully addressed in power sector development strategies, as explained in the World Bank's Environmental Assessment Source book [27].

EIA is an essential part of planning for power sector expansion and for individual projects because social and environmental issues - in their complexity, variety and scope - can be inter-sectoral, inter-regional or even international. Owing to the significant social and environmental impacts of large thermal, hydro and transmission line projects, a comprehensive EIA normally is required by international, and sometimes by national or commercial, financial institutions as a part of their process for reviewing and approving loans. EIA for individual projects should cover the following areas:

- Policy, legal and administrative framework within which the EIA is prepared;
- Project description in a geographic, ecological, social and temporal context, including any off-site investments required to support the project (e.g. pipelines, transmission lines);
- Pre-project data on the physical, biological, and socio-economic conditions in the project area, as a baseline for evaluating impacts caused by the project;
- Social and environmental impacts (positive and negative) that are estimated to occur as a result of implementing the proposed project, proposed cost-effective measures to mitigate potentially significant impacts to acceptable levels, and estimates of residual impacts that cannot be mitigated;
- Analysis of alternatives to the proposed project, in terms of comparative costs, benefits and environmental impacts, providing a justification that the proposed project is the most suitable for implementation;
- Environmental protection management and training programmes already in place or planned to be implemented, including programmes for emergency response in the unlikely event of a major accident that would have off-site consequences;
- Plans for monitoring compliance with health and environmental protection standards and regulations, including what will be monitored, by whom and at what cost.

Sectoral EIA can be used to examine the cumulative impacts of multiple projects to be implemented within a multi-year power development programme. For example, EIA could be used in the electricity sector to study the costs and benefits of an overall programme including: construction of three coal-fired plants and two major hydropower projects; upgrading electricity transmission and distribution systems with the objective of reducing energy losses; and introducing manpower training programmes aiming towards plant management, operation and maintenance. Sectoral EIA can be applied to individual large projects, each of which require a full project-level EIA, or to a group of small projects (e.g. diesel plants or small run-of-river hydro units) that may not warrant individual EIAs. In some cases, a sectoral EIA can substitute for project specific EIA by producing overall guidelines and criteria for the design and implementation of projects in the sector. More frequently, a sectoral EIA will result in identification of the major environmental issues that have to be addressed in the sector and lead to establishment of data bases in support of EIA, thereby enabling project specific EIA to proceed more expeditiously.

There are good reasons for dealing with regional and global issues separately from local issues and ensuring that each is dealt with in the most appropriate context. Regional and global environmental impacts tend to be the subject of national regulations and international agreements, whereas EIA tends to focus on a more detailed analysis of local concerns, such as pollution, visual intrusion and noise in the vicinity of the project. It is, however, important to ensure that projects implemented locally are acceptable within the overall framework of regional and international commitments.

4.5.2. The impact pathway approach

The effects of a given activity can be defined through the chain of relationships, called the 'impact pathway' (Figure 4.5), linking the origin of an *environmental burden* to the *impacts*. A comprehensive assessment of the impacts from an energy system requires the analysis of a multitude of different impact pathways, and must address social and environmental issues at the local, regional and global levels. In addition to immediate impacts, delayed and cumulative effects may be important. Coverage of the full energy chain requires consideration of fuel extraction, preparation, electricity transmission and distribution, waste processing and disposal, as well as the electricity generation process.

Environmental burdens of a facility include the physical and visual intrusion of the structures as well as effects arising from operation of the facility. The latter include routine or accidental discharges to air or water and waste disposal. The burdens produced by alternative generating

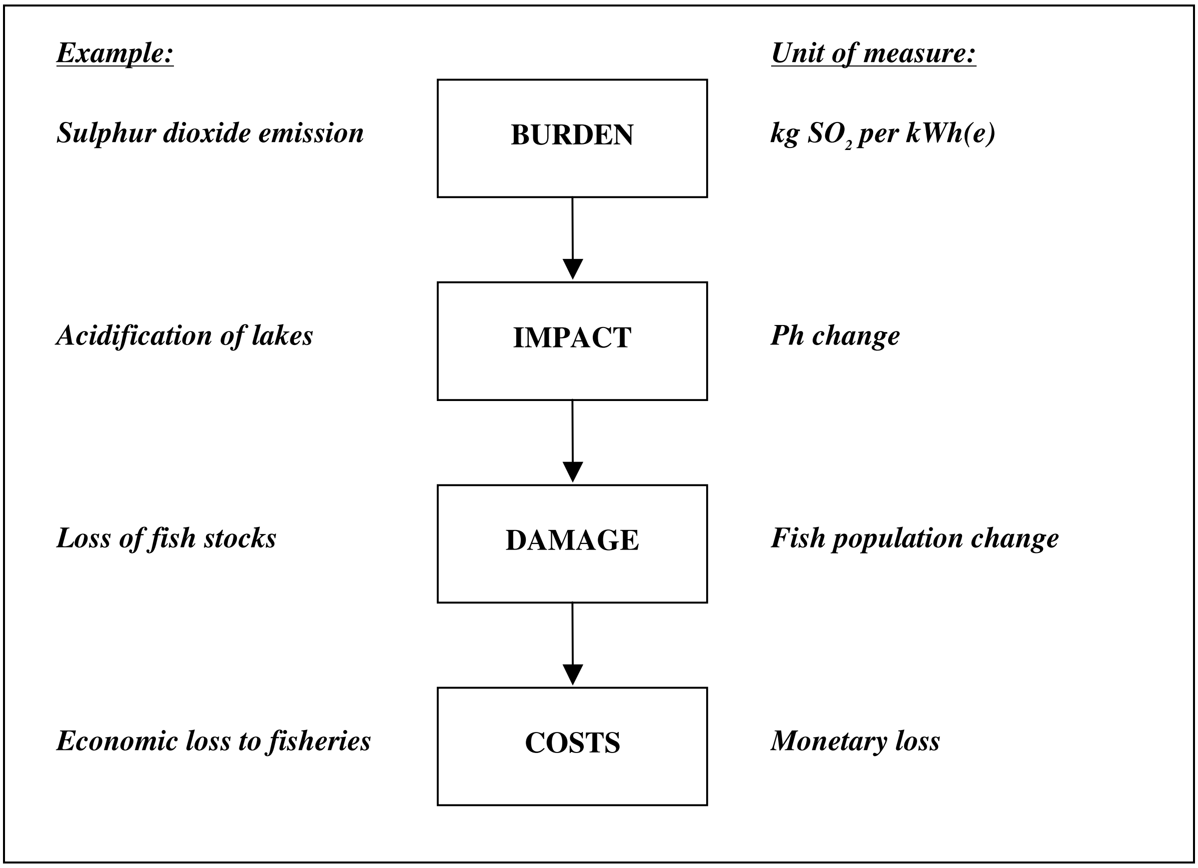


FIG. 4.5. Impact pathway for evaluating environmental impacts.

technologies are not fixed, but are functions of the resources expended to reduce them. Allocation of resources is a policy decision which varies between countries, particularly between groups of countries at different levels of development. Economic and technical limitations to the elimination of emissions and waste products from electricity generation mean that there always will be residual burdens from any fuel cycle. The key point is that the residual burdens should be sufficiently low that they do not cause significant social and environmental impacts.

Impacts are the effects caused by interaction of the burdens with the existing environment, human beings, other forms of life and materials. Impacts may include damages caused to valued heritage and cultural features (e.g. acid rain erosion of historical buildings and monuments). Pollutants are moved along natural pathways and become dispersed in air or water, and may interact with atmospheric, aquatic, or biological systems. Impacts may be caused at any point along the pathways, ranging from local to regional and global impacts. The impact-burden relationships will be site specific as far as local impacts are concerned, but usually are not strongly site specific for regional impacts and even less so for impacts at the global level. Effects may be caused by the primary pollutant emitted, or may be due to a secondary pollutant produced through interaction of the pollutant with the natural environment. Some impacts may be more be more strongly connected to one part of the fuel chain than to other parts. Table 2.1 in Chapter 2 summarises the principal types of environmental, health and social impacts arising from activities in the power sector. These are discussed in detail in the publications from the symposia cited in references 4 and 5 and in annex III. Some important points are described briefly below.

4.5.3. Impacts of different energy sources

4.5.3.1. Greenhouse gases and global warming

The earth's atmosphere contains a range of natural greenhouse gases (GHGs), predominantly carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and water vapour. These gases allow radiant energy from the sun to pass through to the Earth's surface, but they absorb longer wave length heat radiated towards space from the Earth's surface. If the GHGs were not present in the atmosphere, the average temperature on Earth would be some 33°C lower than it is today [28]. Emissions from a large variety of human activities, in particular the combustion of fossil fuels, increase the concentrations of the natural GHGs in the atmosphere, leading to the so-called 'human greenhouse effect'. The main contributor to the human greenhouse effect is CO_2, owing to its large share in total emissions from human activities and to its long atmospheric lifetime (it takes about 120 years for CO_2 released into the atmosphere to be removed by natural processes). Methane is more effective, per quantity released to the atmosphere, than CO_2 in causing global warming, but it is considered to be of lower overall significance because of the much lower quantities released.

The major human activity that releases CO_2 into the atmosphere is the combustion of fossil fuels. The average atmospheric concentration of CO_2 remained little changed over a period of more than 10,000 years, since the last ice age, until the onset of industrialisation in the late 18th century. Since that time, CO_2 concentration in the atmosphere has risen from 280 parts per million (ppm) in the mid-1800s to over 350 ppm in 1990, and the concentration is continuing to increase by about 0.5 per cent per annum [28].

From comparisons of the observed historical changes in the global mean temperature with estimates made by simulations carried out with sophisticated computer models, the Intergovernmental Panel on Climate Change (IPCC) has stated that: the observed temperature rise over the last century (0.3^oC - 0.6^oC) is unlikely to be entirely due to natural causes; a human greenhouse effect is identifiable in the climate record [28]; and this effect will grow with expanding population and higher standards of living. Based on their 1992 emission scenarios, the IPCC projects an increase in global mean temperature of 0.8^oC - 3.5^oC by 2100.

The resultant temperature changes are likely to induce alterations in climate zones and cause the sea level to rise. These changes lead to direct social, health and environmental risks, such as the spread of tropical diseases into temporal zones and flooding of low lying coastal areas. They are forecast also to change precipitation patterns and soil moisture. Hence, agriculture and ecosystems [29] could be affected. Climate zones could shift dramatically over the next 50 years [30]. Changes in climate extremes could be more significant than changes in average temperature and rainfall [31]; for example, coastal floods due to increasingly frequent storm surges could have more impact than a gradual rise in sea level.

In addition to changes in mean climate conditions, the *rate of change* of climate is considered to be of particular importance. If temperate climate zones were to move towards the poles at too fast a rate, flora and fauna would not be able to migrate sufficiently rapidly and some species might disappear. Some researchers suggest that, in order to minimise the risk of climate change, efforts should be made to avoid rates of temperature increase of more than 0.1°C per decade [32], whereas the rate of temperature rise corresponding to the IPCC studies cited above could be as high as 0.3°C per decade [28].

All of these climate change study results are uncertain as to timing, magnitude and regional patterns of temperature change and regarding the probable effects that would be caused by global warming. However, if the average global temperature would rise 2°C above the present level, which already is 0.3 - 0.6°C above pre-industrial levels, the temperature would exceed the highest average temperatures that the Earth has experienced during the entire time that humans have existed [33].

The foregoing discussion makes the implicit assumption that climate change will be progressive, with the changes (both absolute and as rates) being related simply to the cumulative concentrations of GHGs in the atmosphere. However, many scientists [34, 35] have warned that there could be sharp discontinuities in the relationship between GHG concentrations in the atmosphere and climate effects. For example, owing to the fact that global warming influences complex meteorological systems involving ocean currents and polar ice caps, a critical point could be reached at which abrupt climate change would occur. Such 'non-linear' behaviour presents the possibility of catastrophic and irreversible changes, the consequences of which would be immense, although their probability of occurrence is almost impossible to assess.

4.5.3.2. *Acid deposition and chemical oxidants*

Acid deposition and chemical oxidants are treated together, owing to the fact that they interact synergistically and their impacts are to the same targets. *Acid deposition impacts* are caused mainly by rainfall contaminated with sulphuric acid (H_2SO_4) and nitric acid (HNO_3) in solution. These acids result from chemical transformation in the atmosphere of SO_2 and nitrogen oxide (NO and NO_2, known collectively as NO_x) emissions from fossil fuel burning. The impacts include effects on human health, buildings, agriculture, forestry, fisheries and natural ecosystems. Health impacts are probably the most important of all fuel cycle impacts, but are also the most difficult to measure. Acid aerosols associated with particulates and ozone have been identified as being responsible for the principal air pollution impacts from power plants. There are great difficulties and uncertainties in estimating dose-response functions and in designing actions to avert the impacts. The literature on health impacts is strongly dependent on studies carried out in the US, which suggest that there are no safe pollution thresholds for these pollutants. This is a pragmatic, conservative approach comparable to the linear dose-response (i.e. no threshold) approach taken in the nuclear industry in regard to the health effects of radiation.

The biological impacts of acid deposition depend on the characteristics at each site. Effects are long lasting, and not in simple proportion to the amount deposited. This has led to the development of the concept of 'critical load' as an indicator of the potential harmful effects from pollutant gases. A critical load is defined as the maximum quantity of a substance, falling on a given area over a given period of time, which a specified part of the local environment can tolerate without adverse effects occurring [36]. There are continuing scientific uncertainties associated with critical loads, which may be causing future acid rain damage to be underestimated because of the way in which critical loads are averaged over large areas.

The United Nations Economic Commission for Europe (UNECE) adopted the critical load concept for the recent revision of their protocol for the control of emissions of sulphur [37]. This protocol commits the signatory nations to rather stringent targets for the reduction of total sulphur emissions, but even under these reductions a number of vulnerable areas still will be subject to acid deposition rates greater than their critical load, implying that some level of damage is being accepted under the protocol.

Sunlight can promote reactions between a large variety of chemicals in the atmosphere. For example, the most important pollutants involved in the sunlight promoted production of 'photochemical smog' are NO_x, volatile organic compounds (VOCs) and carbon monoxide (CO). These reactions can generate a range of toxic products, principally ozone. Ozone concentrations frequently are strongly dependent on emissions from the transport sector.

The impacts have been studied extensively in recent years, and the main direct impacts have been identified as: effects on human health; damage to materials; reductions in agricultural and forestry yields; and damage to terrestrial ecosystems. The concentration of photochemical oxidants is not in linear relationship directly with the concentration of individual pollutants. The marginal physical impacts and external costs will depend therefore on the background level of pollution.

4.5.3.3. *Particulate emissions*

Some components of power station emissions can be dangerous to human health at very low concentrations. There are numerous suspected hazardous pollutants, and knowledge about their sources, effects and dose-response relationships is still developing [38].

Polycyclic aromatic hydrocarbons (PAH) and benzene are both carcinogenic and are emitted from fuel extraction and processing, and from the power plant through incomplete combustion of hydrocarbon fuels. The numerous trace elements - including arsenic, mercury, beryllium, vanadium, nickel, lead manganese, cadmium and chromium [38] - are contained in fossil fuels and some of these materials are released to the environment in the emissions from power plants. The trace elements are contained primarily in the particulate matter (fly ash) that results from combustion of heavy fuel oil and coal. The concentrations emitted vary considerably depending on the original concentration of the elements in the fuel and the particulate removal efficiency of the filtration equipment on the plant.

Air pollution resulting from sulphate and small particle emissions from coal fired power plants can lead to reduction in lung function, and this reduction can reach critical levels in older people and those who already are suffering from some type of pulmonary problems. As a consequence, sulphate and small particle pollution can lead to the occurrence of fatal pulmonary ailments at an age earlier than would happen in the absence of such pollution. A review of a number of epidemiological studies [39, 40] concluded that the number of people who die early (i.e. have their lives shortened) is equivalent to some 100 deaths per GWe-year of electricity produced by coal-fired power plants. The author of the cited references concludes that this health effect dwarfs all other health problems from fuel use.

Particulates also are the primary cause of atmospheric haze and impaired visibility. The severity of visibility impairment caused by particulate emissions varies strongly with terrain and atmospheric conditions in the vicinity of the power plant. Therefore, it is difficult to apply in one place the measurements or calculations of the level of visibility impairment at another place. Furthermore, the acceptability of a specific level of visibility impairment will differ from place to place, depending on existing air quality, population densities and public preferences.

4.5.3.5. Releases of radioactivity to the environment

The nuclear energy chain for electricity generation involves the release of small amounts of radioactivity in a variety of forms to both air and water. The primary impact associated with these releases is considered to be the potential health detriment associated with exposure of the human population to the released radioactivity.

International standards for the maximum permissible radiation exposure of both nuclear industry employees and members of the public are recommended by the International Commission on Radiological Protection (ICRP). The most recent recommendations, in ICRP60 [41], stipulate a maximum radiation dose for members of the public of 1 milli-Sievert (mSv) per year. Some perspective on these upper limits or constraints on the public radiation exposure resulting from nuclear facility discharges of radioactivity is provided by the exposure which results from natural background radioactivity. Doses from natural radioactivity in Europe are, on average, around 2 mSv per year. There is substantial variation from place to place, such that individual doses from natural radioactivity range from 1 mSv per year to well over 10 mSv per year [42]; that is, up to ten times higher than the recommended maximum exposure that would result from nuclear facility emissions of radioactivity.

The effects on health which result from exposure at these low levels can be only estimated, owing to the fact that the effects are too small to be measured. For purposes of making estimates, it is assumed that there is a linear relationship between *exposure* to radiation and the *probability* of subsequent health effects, amongst which the most important are possible fatal and non-fatal cancers. This linear dose-response relationship assumes that there is no threshold of dose below which the probability of effects falls to zero. Thus, even when the level of dose is very small in comparison to the dose received from the natural background radiation, it is assumed that the dose would represent a small, but calculable, health detriment.

Although the limitation on maximum individual dose is central to the regulation of emissions, individual doses (at the levels indicated above) are of little significance in the assessment of overall detriment. All but a few members of the population receive doses that are one or more orders of magnitude lower than the maximum individual dose limit. However, the ‘linear hypothesis’ applied in radiation protection assumes that radiation doses to an individual are associated with a stochastic risk of subsequently incurring a health detriment, principally cancer or genetic damage; the magnitude of the stochastic risk is proportional to the radiation dose and, although very small, is never zero.

The summation of small individual doses over a large population produces the 'collective dose' to the whole population. Following the linear hypothesis, the risk factor described above for individuals may be applied to the collective dose to arrive at an estimate of the total number of health effects that would expected within the population. It should be stressed that such estimates are speculative and possibly are very pessimistic, because they depend entirely on the validity of the 'linear hypothesis', which assumes that there are some health effects even at vanishingly small levels of radiation dose.

Particular difficulties arise in defining the population groupings and time periods over which collective doses should be evaluated. Theoretical models allow calculation of the collective dose to the entire world population, due to emissions from an individual nuclear installation anywhere in the world. Similarly, when calculating collective doses from emissions, it is necessary to take account of the persistence of radio-nuclides in the environment long after their discharge or disposal; this is expressed by the 'integration period' over which collective doses are calculated. Thus, for long lived radio-nuclides, there are theoretical grounds for calculating collective doses over an integration period of thousands or tens of thousands of years. However, the combination of long integration periods and growing world population can produce apparently high collective doses, and hence large health detriments, which have little physical reality because of the infinitesimally small levels of individual doses involved, in particular when compared to the collective dose from the natural background over the same integration period and population.

4.5.3.6. Water pollution

Thermal power stations can have effects on water quality primarily through cooling system warm water discharges that may alter the aquatic ecology of the water receiving the discharges, through changes in the water temperature and density and in the solubility of oxygen in the water. Higher temperatures also increase the metabolic activity of organisms, including some that are potentially harmful pathogens. Thermal pollution is, however, now considered to be much less important than other pollutants [43], owing at least partly to the fact that many thermal power stations are equipped with cooling towers. However, cooling towers can have a significant visual impact, owing to their large size and height and to the highly visible moisture plume. Thermal power stations also affect aquatic ecology by killing fish that become entrained with the intake of cooling water.

Liquid discharges from thermal power stations also may be contaminated with other materials; for example, discharges from nuclear power stations contain very small quantities of radioactive substances. Fossil-fuelled power stations can have serious effects on water quality through leaching of contaminants from fuel ash and from FGD treatment residues.

4.5.3.7. Solid wastes

The disposal of solid wastes, including sludges, requires significant areas of land substantial operating costs. Waste disposal costs are included as part of the power station operation and maintenance costs, and are, therefore, internalised and included in standard procedures for comparing generation costs of different types of power plants. However, even well-controlled disposal operations have some residual environmental impacts, such as those associated with land use, visual intrusion and low level emissions from the disposal site. There is a requirement for strict control and monitoring of waste transport and disposal operations, particularly when dealing with toxic wastes. The disposal of radioactive waste receives special attention because of the possible risk of radioactive materials escaping into the environment.

4.5.3.8. Visual amenity

Land usage and visual intrusion are important considerations in siting power stations. Visual intrusion is particularly important with respect to large buildings, chimneys and cooling towers at thermal power stations, and also for some renewable energy systems, such as wind farms in which tall, large diameter wind turbines are distributed over large areas. The level and perception of visual impacts depend on the scenic values of the area in which the project is located and on the attitudes of the local public.

4.5.3.9. Social and economic factors

External effects are important not only in terms of the environment, but also in terms of employment, resource depletion, cultural issues, etc. [44]. Employment benefits may play a particularly important role in times of high unemployment. They influence the level of private income and impact on government expenditure on social security. Employment effects can also have significant consequences on a country's trade balance through import substitution. Whilst impacts on monetary issues (e.g. costs incurred by the government, such as induced public expenditure and lost taxes) are, in theory, easier to measure than the impacts on non-monetary issues (e.g. the environment), there remain major problems owing to the inter-dependencies of public responsibilities and the resulting expenditures. Also, it often is difficult to identify the specific causes of particular external costs, whether monetary or non-monetary.

External economic effects may be incurred also when depletable natural resources are not priced according to their long term scarcity but only on the basis of the extraction costs of the resources currently being exploited [44]. Optimal allocation of depletable resources implies that their present use will not lead to external costs for future generations. This situation leads to difficult questions over whether to exploit the resource today, and invest the revenues in options for the future, or to conserve the resource for use in the future at which time it may have a greater value or no alternatives.

Involvement of IAPs is important in order to understand the nature and extent of potential impacts, especially those of socio-cultural nature, and to assess the suitability and acceptability of various measures that might be used to prevent or mitigate impacts, or to compensate affected groups for those that cannot be avoided. Involvement of IAPs is useful also in the analysis of the distribution of project costs and benefits. Moreover, a genuine effort to provide the public with information about a project, and to solicit public reactions and suggestions for alternative solutions, leads to projects that are more acceptable to IAPs, and more likely to be supported by them.

Consultations with IAPs can take several forms and can involve different approaches and methods, varying from public meetings and focus groups to individual interviews. The most suitable approach will vary with the social and cultural context. Where public officials and ordinary citizens are accustomed to interacting freely and having their statements and opinions challenged and debated, the process of consultation can take place in open public meetings. In many developing countries, however, public meetings of this kind are unfamiliar or uncomfortable for both citizens and public officials. In such settings, public meetings could lead to counter-productive results, such as passive hostility or the appearance of consensus where none exists.

Informed views of diverse segments of the affected population, including indigenous peoples, are critically important to the EIA process because different groups use and are familiar with different parts of the environment and will be affected to different degrees by power stations, in particular large hydropower projects. For example, men often are not well informed on the environmental resources that women use for domestic or income producing purposes (e.g. wood gathering in developing countries). Shopkeepers, farmers and traders in contact with indigenous people may appear knowledgeable to an outsider, but only the indigenous people themselves have accurate information about social changes which affect them and the natural resources they use.

4.5.4. Comparison of impacts

Analysis and comparison of the environmental impacts from different energy sources are complicated by a number of difficulties. For example, the inter-dependencies between time and space dimensions of impacts are not fully known, are often overlooked and are difficult to normalise on a common scale useful for comparisons. The requirement to include long term future effects, as well as immediate or short term effects, involves issues of inter-generation equity. Detection of linkages between exposure and damage is also difficult in many cases. The functional form of dose-response relationships will vary among different pollutants and different receptors. In some cases, it is reasonable to assume a linear dependence without any lower zero-damage thresholds, but this is not valid in all cases. Different technologies impact differently on vulnerable receptors, i.e. specific biota, ecological habitats, or particular physical or chemical environments.

If the site specific approach is taken to evaluating the environmental impacts of generation projects, using the impact pathway methodology shown in Figure 4.5, it will require a very large volume of work. Therefore, this approach may be impractical when studying problems associated with the full energy system or the electric power system, owing to the wide range of factors that need to be examined if an impact pathway is to be fully understood. This requires the following detailed stages of analysis:

- Preparing data describing the characteristics of the system (technologies, fuels, reliability, emission abatement systems) and the site;
- Estimating the quantities of emissions and other potential burdens. This relies heavily on the quality of data collected in the first stage of the analysis;
- Describing the transport of pollutants and the processes of physical/chemical transformation of pollutants. The use of a range of different models is necessary in order to understand the interactions in this stage;
- Identifying and describing quantitatively the doses received, populations affected (critical groups) and sensitivity of ecosystems (critical loads);
- Understanding and estimating dose-response functions (e.g. mortality rate, loss of agricultural production, corrosion). These can be complicated by dose-effect thresholds and synergisms among different pollutants;
- Determining the magnitude and value of any damages caused.

In practice it is not feasible to determine, at the outset, the whole range of environmental damages resulting from all fuel cycles on a location-specific basis. Consequently, a more feasible approach is to use results from existing studies and to adapt those results to the specific situation by applying systematic factors (e.g. generalised damage functions and dose-effect coefficients). However, having in mind the complexity of the EIA process, this generic approach for ascribing environmental coefficients to energy resource activities frequently is associated with large uncertainties and does not allow for location specific aspects to be represented fully. When deciding which approach to take, it is necessary to balance the amount of resources available for the study and the required accuracy of the study results.

Methods for making comparisons of the environmental impacts of different energy sources are not well developed, although there are several which can be useful:

- *Ranked environmental assessment.* Use of ranking assessment procedures is well developed in environmental impact assessment generally. Fuel cycles are broken down into their components and the impacts from each component are ranked and displayed in an attempt to identify the major impacts that need further attention.
- *Emission values and ambient quality indices.* By normalising emission values to quantities per unit of electricity generated, the emission values can be utilised to characterise environments in terms of various factors so that the overall quality indices can be obtained.
- *Critical loads and critical levels.* The critical load and critical level concepts, as discussed in Section 4.5.3.2, has been applied to ecosystems in an attempt to set limits to environmental burdens, above which damage is expected to occur. If information is available on how far the critical loads are exceeded, then this can be taken as a qualitative measure of the severity of impacts on the environment. Estimates of critical loads can be obtained from empirical relationships, historical dose-response data and process models of the environment.

Comparative environmental assessments provide decision makers with an important basis for incorporating environmental and health impact considerations into electricity generation planning and decision making. The fact that uncertainties exist does not invalidate comparative assessment as a useful tool. However, comparative environmental assessment has had only limited practical influence on the decision making process up to now, although it has allowed the full range of issues to be presented in an unbiased way. The DECADES Project [24] has started to draw together an international framework of data bases and methodologies for comparative assessment of different energy sources for electricity generation. This project is a valuable source of information to support the integration of environmental and health effects into the comparative assessment of different energy sources and alternative scenarios for electricity production, and for relating the alternatives to the socio-economic context in which they are envisaged to be implemented. In order to facilitate the evaluation and comparison process, it is desirable to put a monetary value on the different environmental impacts so that they can be compared on an equal basis. This concept is discussed in Section 4.6.1.

4.6. Valuation and incorporation of external costs

4.6.1. Why calculate environmental costs?

The environmental, health and social impacts from electricity generation affect different populations, including sometimes people who do not get the benefit of the electricity produced. There is a need for planners, decision makers and IAPs to identify the best solution from a range of feasible alternatives, taking due account of different issues during the judgement process. It is helpful to express all external costs in a single figure of merit (e.g. total monetary value of damages), but differences in site specific impacts raise questions about transferability of cost estimates from place to place. Ideally, cost estimates for each technology would be based on a set of hypothetical locations in the country of interest, in order to reflect the spatial distribution of burdens and the types of entities at risk. Discharges or impacts via accidental events are of interest as well as those associated with normal operational activities. Interest in the use of external environmental damage costs, as 'adders' on top of internalised environmental protection costs, is increasing among regulators and policy developers. The evaluation and application of 'adders' is now the subject of study and assessment by a variety of agencies and academic bodies in Europe and the USA.

There are several ways in which externalities, once they are known, can be integrated into resource planning. As well as direct monetisation, externalities may be subject to 'rating and weighting' to produce a composite 'score', including allowances for other resource attributes (e.g. supply reliability, operation costs). Other approaches involve simple qualitative judgements or rule based methods, such as giving credit to generation technologies that are not based on combustion of fossil fuels. The strengths and weaknesses of these methods have been discussed by the Electric Power Research Institute [45] in the USA.

There is growing support for moves towards the 'full cost pricing' approach, with the implicit or explicit expectation that market forces would deliver environmental and social benefits in a way that maximises economic efficiency. Explicit monetisation of a wide range of environmental impacts allows the damages to be expressed as costs per unit of energy produced. This allows direct and consistent comparisons between: external costs and conventional internal costs; different contributors to external costs; and different fuel cycles and generation technologies.

However, there are difficulties with the practical application of this approach. For example, the optimum abatement level occurs when the marginal internalised cost of abatement equals the marginal external environmental damage cost. This raises a number of questions that presently are being wrestled with, such as how to proceed if the external damage cost is not known or how to deal with the damage costs of residual discharges, if other conditions are close to optimum.

Various authors [e.g. 46, 47] indicate that, despite such difficulties, quantification and monetisation of external environmental costs is likely to lead to better decisions, and that, on balance, society is likely to be better off than would be the case if external costs are not used in the decision process. There is potential for pitfalls, however. For example, the incorporation of external costs for new plants, but not for old plants, could have the undesirable effect of delaying the replacement of less efficient and more environmentally damaging older plants [48].

4.6.2. Different approaches to costing environmental effects

Three different approaches to costing have been used as measures of the environmental effects of energy consumption:; (i) abatement costs; (ii) mitigation costs; and (iii) external environmental damage costs.

Abatement costs are those arising from the installation and operation of equipment for preventing or reducing potentially damaging discharges to the environment. They include, for example, the costs of filtration systems and the costs of safe disposal of waste arisings.

Mitigation costs arise when environmentally harmful emissions or potentially harmful activities are permitted, but action is taken to reduce or compensate for the consequences. Examples include: ‘creative conservation’ projects to recreate, or replace at another location, wildlife habitats destroyed during construction; adding chemicals to lakes as a means to offset acidification; planting trees to absorb carbon dioxide emissions; and building dikes to protect low lying areas against sea level rise.

Economists indicate that *external environmental damage costs* are the correct basis for comparing technologies, although abatement costs and mitigation costs are quoted in many studies where the circumstances make it impossible to assess environmental damage costs. However, it would be erroneous to attempt to arrive at an estimate of external environmental cost without distinguishing clearly among the three distinctly different types of cost (i.e. abatement, mitigation, damage). Each type of cost has to be assessed separately. In particular, it would be a mistake to use abatement or mitigation costs as proxy estimates of damage costs.

In practice, however, the situation is less clear cut. The knowledge of costs of damage, abatement and mitigation is extremely imperfect, and important cost elements may be missing due to the lack of scientific information. In some cases, industries have yet to discover or invent ways of abating or avoiding pollutant releases; incentives need to be given for encouraging the necessary research. Mitigation may involve property or land not owned by the polluter, and the property may even be in another country (e.g. for the replanting of forests to absorb CO_2). Present mechanisms for promoting and/or supporting the mitigation of environmental damages may not be adequate for dealing with mitigation measures on such ‘remote’ property. In the absence of general agreements among all countries regarding measures to combat pollution, the adoption of strict environmental protection measures by some countries could encourage polluting industries simply to migrate to areas where protection policies are less severe.

4.6.3. Valuation of environmental damage costs

4.6.3.1. The concept of valuation

Environmental damages to some receptors can be estimated in economic terms without major difficulties, owing to the fact that the receptors are traded as marketed commodities. For example, the economic value of a measured loss of a crop yield or the cost of restoring acid rain damage to a building, can be established by using information on the market prices of the commodities involved. The changes in market supply and demand for the commodity can be determined and hence the effect on the price and the quantity sold can be estimated. This information allows environmental costs to be computed or measured in terms of the reduction in consumer plus producer surplus [49]. However, this economic approach does not allow to ‘internalise’ non-market environmental costs, such as the aesthetic values that individuals may place on a pristine environment or on maintaining the unaltered character of historic buildings or ancient monuments.

Attempts to estimate these non-market environmental costs will produce confusing results if viewed solely in terms of conventional measures of economic progress, such as Gross National Product (GNP) indices. Pearce points out [50] that GNP largely ignores environmental assets and treats them as if they have a zero or near-zero value. Therefore, Pearce argues that the measures of economic progress need to be changed, because GNP fails to measure the true ‘standard of living’. In order to estimate the environmental costs of energy technologies, it is necessary to develop a comprehensive and consistent methodology (within the limits of the accuracy required for decision making associated with the principal environmental risks concerned) that enables a reasonably acceptable expression of the 'quality of life', in economic terms that are broader than the conventional definition of 'standard of living' as measured by GNP indices.

Amenity costs may be determined partly through studies of the values that society places on the use of environmental assets. Public preferences for a higher quality environment, for example in residential areas, can be determined through hedonic pricing studies; similarly, travel cost methods can be applied to determine values placed on the use of recreational sites. However, contingent valuation is the only method for valuing all aspects of the environment.

Hedonic property prices. Economists have long recognised that the value of a piece of land is not determined solely by its utility purposes, such as the agricultural output. Other factors that can be important in the measurement of value include, for example: access to workplace, recreation facilities and other amenities; environmental quality of the neighbourhood; presence or absence of nuances (e.g. noise, air pollution) caused by traffic, airports and industrial facilities. The hedonic price approach attempts to identify the value of such factors, by inferring how much consumers are willing to pay for an improvement in the environmental quality and thereby determining the social value of this improved quality [50].

Wage/risk studies. The wage/risk study approach is based on the assumption that wages can be used as a proxy for the individual's aversion to real or perceived accident or health risks in the workplace. Examining wage markets can reveal the presence of risk premiums in wages paid to workers in risky jobs as compared to wages in less risky jobs, thereby revealing the willingness of workers to be compensated for accepting the risks associated with their job.

Travel cost approach. The travel cost approach attempts to estimate the benefits of environmental improvements in recreational facilities such as parks, lakes or forests. The underlying idea of this approach is to find out how much money and time people actually spend to travel to a particular recreational site, as a basis for estimating their willingness to pay for maintaining the facilities of that site. This information then can be used to derive the site value. It also facilitates the evaluation of the changes in such sites brought about by environmental improvements or degradation. The travel cost approach can be regarded as a useful tool to establish the value of recreational benefits, but is inappropriate for application to valuation of other goods.

Contingent valuation. Contingent valuation (CV) methods rely on survey techniques to elicit expressed personal preferences. Individuals are asked how much they would be willing to pay (WTP) to avoid hypothetical scenarios that involve reduction in health or environmental risks or impacts, or conversely, how much they would be willing to accept (WTA) by way of compensation (see wage/risk studies above) for accepting such reductions [51].

The principal disadvantage of CV is that it is subject to biases that are very difficult to control or even to identify. Respondents may reveal preference because of various reasons (e.g. strategic or commercial purposes, increased personal influence). However, improved design of the questions used in the surveys can help to overcome this disadvantage. Respondents taking part in surveys have to be familiar with the environmental commodity in question, and they have to be familiar with the hypothetical means of payment. In order to reduce biases further, it is necessary to provide respondents with information that is sufficient to enable them to form their own opinion [50].

The advantage of CV is that it, technically, is applicable to all circumstances [51] and is a consistent approach for valuing environmental impacts. CV is capable of deriving both WTP and WTA estimates and of putting prices on potential future environmental risks, such as global warming and nuclear accidents.

However, many other impacts concern items which are not commercially traded, so their value is not easily measured. In fact, this category includes many intangible factors, such as loss of species diversity, ecosystem preservation and visibility. Many of these impacts will have isolated or unique impacts, rather than widespread effects. There is a need to focus on the valuation of these intangibles, as they often appear to represent a large component of the real concerns. However, even contingent valuation may not give satisfactory valuation of such environmental impacts as destruction of rain forests, ozone depletion and climate change, which have major implications for human welfare. This is because many of the services from the ecosystem are not fully understood, and therefore may be excluded in the WTP valuation of individuals.

Whereas an individual can imagine changes in factors such as air or water quality, and in a hypothetical framework, can attach monetary values to specific amounts of change in the attributes, most individuals cannot be expected to have sufficient information to place a monetary value on the implications of global warming or loss of bio-diversity. In fact, even expert understanding of the working of the ecosystem is so limited that no one is likely to be able to make even approximate estimates of the stream of services generated by ecosystem attributes such as species diversity. Existence value, which often actually is higher than use values, may nonetheless be attributed a quite low value by individuals, owing to unfamiliarity with less accessible ecosystem components such as the benthic layer of oceans.

Yet, it is only through CV that it is possible to determine the values that society places on environmental assets beyond those available for their own use (i.e. non-use values). Non-use values are derived through examination of society's appreciation of three distinct further forms of environmental benefits: option values, bequest values and existence values. *Option values* are attached to those environmental assets which an individual currently may not use but nonetheless values for potential use in the future. *Bequest values* apply to cases where an individual may neither currently use an asset nor desire the option to use it in the future, but nonetheless attaches a value to bequeathing this asset to future generations. Finally, *existence values* relate to environmental assets that may not be valued for their current use nor for bequeathing to future generations, but which nonetheless may be highly valued simply for their own existence.

In practice, the total amenity values of non-market environmental assets derive from a combination of their use and non-use values, and the importance of the different components will vary considerably with the feature under consideration and the part of society making the value judgement. For example, an urban recreational park probably will have a very high use value but may not warrant a comparably high existence value. In contrast, internationally protected wilderness areas or tropical rain forest ecosystems with a high biodiversity may have very low use values, but, perhaps by definition, will command extremely high existence values. Therefore, no simple system can be used for the determination of differing environmental amenity values. Detailed contingent valuation research is required for the comprehensive assessment of the environmental costs of impacts associated with energy technologies.

4.6.3.2. Problems with valuation

Annexes III, IV and V illustrate that the volume of research in the area of environmental analysis is growing rapidly; however, there still are gaps in the data and the information that is available tends to be of very variable quality. Cost estimates based on data specific to a certain location often are applied to other locations where the costs may not be appropriate. In some cases, the value judgements of individual researchers have been used selectively, although such judgements differ among researchers. Uncertainties exist at each stage of the process but are most significant at the valuation stage.

Some impacts, such as damage to buildings and loss of agricultural production, are effects on items which are traded in the market. For those linked to market effects, monetary valuation is relatively simple, at least in principle. Care is needed, however, to avoid double counting; for example, where an external environmental cost is internalised already through emission taxes or by way of established emission standards. Other impacts concern cultural or amenity values of items which are not commercially traded, so their value is not easily measured. These include loss of biological species diversity, ecosystem preservation, damage to heritage features and recreational zones and reduction in visibility at scenic sites. Such impacts may be locally unique, rather than widespread, and valuations will vary from person to person and place to place, depending on cultural and political circumstances and attitudes. For some technologies, for instance hydroelectric plants or wind farms, these types of impacts may dominate external costs. At present, the most accepted way to address these issues appears to be the CV approach discussed above. This approach has the potential to reveal a consensus, if it exists, on valuation as well as the range of attitudes (range of valuations), though doubts have been expressed about results relating to 'non-use' values, such as the value of biodiversity.

Large accidents such as hydropower dam failures or nuclear accidents, or extreme events such as drought or floods whose effects are made worse by human activities (e.g. deforestation), are a special case. They happen infrequently but have major environmental impacts when they occur. In order to obtain an estimate of the 'amortised cost' of such accidents, the estimated total damage cost (per accident) is multiplied by the probability of occurrence (e.g. accident occurrence probability per GW-year of nuclear electricity production). This yields an estimate of the accident cost per unit of electricity production. The safety standards and regulations applicable to nuclear facilities are designed to limit the risk of large accidents to extremely low levels.

In the case of catastrophic events resulting from climate change, some researchers have attempted to estimate the cost of the damage they could cause. However, there are great uncertainties regarding the probabilities of such events, as well as where and when they might occur. In these circumstances, comparisons of the external environmental costs of different energy technologies could be facilitated by expressing the costs in terms of a 'shadow risk premium'. It is clear that global warming could have both 'progressive' and 'catastrophic' effects. The treatment of damage in these contexts is particularly difficult. The 'risk premium' cost would have to be based on an assessment similar to the CV approach, in order to determine the public's willingness to pay for measures aiming towards reducing a risk or its effects.

A further issue arises out of the long term nature of environmental change. Today's activities may result in harm at some future date, raising the issue of the present generation causing damage whose costs will be borne by future generations. Methods for incorporating such future costs into today's decision making are the subject of considerable scientific controversy. Arguments for and against a zero discount rate have been part of an unresolved debate concerning inter-generation equity and sustainability. If per capita income rises in future years, future generations may exhibit a higher WTP for protecting health and the environment. The discount rate applied to health and environmental impacts therefore needs to represent the difference between a pure discount rate and a rate of appreciation of the relevant value. Discount rate values in the order of 2-4 per cent can be justified on the grounds of incorporating a sustainable rate of per capita growth and an acceptable rate of time preference. However, even these rates can make issues that will occur many decades in the future, such as any potential risks associated with radioactive waste disposal, seem unimportant. Where future damages are difficult to value, and where they could result in the loss of an ecosystem, a sustainability approach should be applied. This requires debiting the activity causing the damage with the full cost (i.e. applying a zero discount rate), or imposing a constraint instead of applying monetary values. For example, if it would be demonstrated that a certain activity would lead to unacceptable and irreversible damages, then the option causing that damage should be excluded (or, alternatively, the damage should be assigned an infinite cost).

Other issues include environmental effects across national boundaries. This raises the problem of determining the extent to which a facility in one country may cause environmental damage in a different country, and to place values on the damages caused. While local factors (e.g. income levels) may produce valuations of damage that vary from country to country, it normally is accepted that damages, particularly to human life, should be valued in accordance with guidelines applied in country in which is located the facility causing the damage, even though the damage may occur in another country.

4.6.4. Concluding remarks on external costs

There is growing support for moves towards the 'full cost pricing' approach, with the implicit or explicit expectation that market forces would allocate environmental and social benefits in a way which maximises economic efficiency. Explicit monetisation of environmental impacts allows the damages to be expressed as costs per unit of energy produced and facilitates direct and consistent comparisons between: external costs and conventional internal costs; different contributors to external costs; and different fuel cycles and generation technologies. No matter what methodology is used for estimating the environmental damage costs of different electricity supply options, it is essential to consider: (a) *completeness*; i.e. have all significant impacts for the full energy chain been covered? (b) *consistency*; i.e. have the comparisons been biased by applying different approaches to different technologies?

Also, it is important to keep in mind the limitations and difficulties involved in valuation of external environmental damage costs. However, the presence of these issues does not mean that the basic concept is unsound or that government policy formulation should ignore residual external environmental costs, even though the cost estimates are uncertain.

4.7. Integration of economic, social, health and environmental impacts

4.7.1. Introduction

The simultaneous consideration of quantitative, qualitative and purely intuitive aspects of a problem is a difficult task. In such an environment individuals, including experts, are liable to introduce a number of cognitive biases. For example, an individual may avoid, intentionally or unintentionally, the difficult problem of value trade-offs by focusing exclusively on a part of the information which is new, easy to understand or compatible with personal preferences or knowledge. In energy policy debates, this may help to explain the emergence of pressure groups that focus on only one of a number of relevant factors (e.g. opposing nuclear power on the grounds of its perceived safety risks while ignoring potentially higher risks with other energy sources).

In such a debate a ‘decision aid’ can be a helpful tool for structuring and clarifying issues and opinions. The tool can help in establishing a common framework for considering all the diverse aspects that are relevant to the problem, and in helping to ensure that no relevant aspects are overlooked. It should also enable to: focus the debate on the real issues; eliminate unimportant issues; and make different value judgements transparent and open to constructive debate. In this way, decision aiding tools could facilitate reaching a compromise through enhanced communication [52].

Multi-criteria decision aiding techniques can assist in a comprehensive and thorough analysis of complex problems as a means of providing decision makers with adequate information for taking difficult decisions. The techniques usually require precise formulation of the decision problem and a knowledge of the decision maker’s preferences. However, this information is difficult to obtain in a numerical form that is suitable for input to analytical models. There may be several decision makers who may have different preferences and the parameters of the decision problem may be ambiguous. Because of the particular difficulties related to defining preferences in numerical form, different methods have been proposed for treating preference information in an imprecise form [53]. The sample problem presented in Annex VIII shows an example of the application of a decision aiding tool (MCITOS) in a real planning exercise.

4.7.2. Multi-criteria decision aiding approaches

The incorporation of economic, social, health and environmental factors into the process of decision making for the electricity sector can be done in various ways. Such factors are routinely considered when decisions are made at the project level, i.e. whether to proceed with a particular power plant. For example, Ontario Hydro has developed a process for evaluating each generation candidate plant (e.g. 4 × 881 MW CANDU nuclear units) with respect to a long list of criteria, including feasibility, cost, planning flexibility, health and safety impacts, natural environment considerations, social and economic considerations and performance [54].

At the policy and system levels, there is a need to consider these factors on broader scales, including regional, national and global implications of electricity system development. France has taken the generating system viewpoint, but does take explicit account of factors other than direct generating cost [55]. In Germany, the pattern of power generation is the result of cost-effectiveness considerations, governmental decisions on energy policy, environmental protection legislation and questions of social acceptability [56]. A recent study [57] concluded:

- Even if there is general agreement that power sector investment planning procedures need to better reflect environmental considerations, exactly how this is to be achieved is still unclear.
- There remains a huge gulf between general discussions of the subject - that typically argue for comprehensive frameworks and the like - and techniques that are operationally practical.
- The literature on the subject of how to consider environmental costs in power systems planning is quite limited - a reflection of the very few attempts that have been made to formalise the process into operational models.

Given that the results of the studies being conducted by analysts often are not to be used by a single decision maker but rather will be presented to a number of IAPs (i.e. regulators, environmental groups, consumer groups, utility management, financial groups, members of the public, etc.), it is important that the studies be systematic, comprehensive, quantitative and understandable. Multi-criteria (e.g. including economic costs, environmental impacts, health and safety effects, technical performance) decision-aiding methods can help analysts and information users to address these concerns. Conceptual methods for considering the several criteria are outlined here.

Two fundamentally different approaches are outlined. Each has advantages and disadvantages with respect to any particular application. The two methods are:

- Simultaneous optimisation approach: include all criteria in an objective function and 'optimise' over all criteria simultaneously, or
- Step-by-step approach: plan the appropriate energy system by simulation or optimisation over a single variable, e.g. least cost, then identify and evaluate the associated impacts, and finally generate other alternatives as necessary to change environmental, safety and social impacts.

Both approaches fit the framework shown in Figure 4.1. The choice of which method to use depends on the specific situation.

4.7.3. Simultaneous optimisation approach

Combining the several criteria of concern into a single unit of measure that can be 'optimised' is the most satisfying, and challenging, from a mathematical point of view. The approach offers the possibility of 'one-pass analysis'; i.e. no iteration through the energy planning models. In this approach, analysts fully describe the problem and all impacts of concern, including value trade-offs, and the model evaluates the alternatives presented, or preferably, generates optimal alternatives. Social, health, safety and environmental impacts may be included directly, e.g. by associating a value (economic or trade-off in terms of another impact or cost) with a unit of impact and/or may be addressed as constraints, e.g. limitations on emissions (these two approaches are sometimes called the 'weighting' method and the 'constraint' method) [57].

A traditional way of addressing at least the existence of environmental and social impacts was through constraints [58]. Use of constraints generally is not very satisfactory because it implies that different levels of impacts, all of which satisfy the constraints, are equivalent in value. For example, if one alternative has sulphur dioxide emissions at the maximum allowable value (the constraint), and a second alternative is the same in every way, except that the total cost is one US$ more while sulphur dioxide emissions are reduced by thousands of tons per year below the constraint, a least-cost optimisation model will select the first alternative, although most IAPs will prefer the second alternative.

Unfortunately, there are a number of practical limitations to including impacts in the optimisation by associating a value with each unit of impact. The previous section (4.6) outlined methods and difficulties of converting environmental, health and social impacts into external costs by assessing damage, abatement and mitigation costs. Value judgements involving human health and safety impacts are particularly controversial. Obtaining ranges for such value trade-offs is less difficult, but optimisation tools generally require a single value. Also, the impacts of concern are experienced at several different geographical levels, which may result in different levels of potential policy interest and intervention, e.g. global, international, national, provincial and local [2].

Converting impacts to monetary costs and including them in the objective function (i.e. internalisation) gives the impression that subjective elements, i.e. preferences for different outcomes, have been quantified, and the problem is now objective and can be analysed in detail. As mentioned above, different levels of policy interest and intervention are likely in any major decision affecting the energy system. The individuals involved in such evaluations typically have different judgements about what is important and what is the value of different levels of achievement with respect to each criterion. In such cases, it is important to be able to easily alter those value judgements.

Even when the impacts have been quantified in terms of external costs, and the optimisation approach is used, there still remains the problem of deriving solutions that are relevant to the appropriate decision maker. For an electricity generating system, there generally is an organisation (electric utility) that is looking for a solution that minimises total costs to the organisation. In such a case, the appropriate external cost to be considered might be the costs the utility must incur to meet legal requirements (e.g. abatement and mitigation costs). Use of damage costs (not paid by the utility) for pollutant emissions that are within legal standards might lead to a plan that is different from the one that is optimal plan from the utility's view point. Thus, a 'societal' optimisation that considers all costs borne by society, and not only the costs borne by the utility, might lead to a different generating system expansion plan. An optimisation model may be helpful in finding that optimal plan, and thereby calling into question whether there should be a policy of recognising the external costs beyond current legal requirements, and, if so, the implications of that policy.

An example of a cost that has been included very effectively in an optimisation objective function is the treatment of unserved energy cost in the IAEA's Wien Automatic System Planning (WASP) Package [22]. The cost of unserved energy refers to costs associated with the expected amount of electrical energy not supplied to customers because of generating capacity deficiencies and/or shortages in basic energy supplies. Consideration of only traditional costs of generating plants (capital, operation and maintenance, and fuel), without considering any value for reliability of service or specifying a required level of service reliability, would mean that very unreliable systems might be chosen because they have lower costs than more reliable systems, although they do not serve fully the demand. One way to address this problem is to determine the least-cost expansion plan that meets a system reliability constraint (e.g. maximum acceptable loss-of-load probability). Another way is to estimate the value of a unit of demand that is not met (energy not served), and include this value in the economic objective function. WASP-III and subsequent versions of the WASP package provide this option, which many analysts find very useful. Setting an absolute reliability standard implies a high value for energy not served, since the model is not allowed to consider strategies that would exceed the constraint. The marginal value of energy not served can be determined by making sensitivity runs with optimisation models such as WASP.

For optimisation purposes in expansion planning for electric generating systems, including the unserved energy cost in the objective function is preferable to a physical constraint on reliability, whenever the value for a unit of unserved energy is known with some confidence. This allows the optimisation model to choose the appropriate level of reliability and assures there are no better solutions with reliability only marginally worse than would be acceptable with the physical constraint. This same procedure could be used for including values for environmental impacts if they could be quantified with confidence.

When the complete fuel supply system is being considered in addition to the electrical generating system, or when the entire energy supply system is being examined, the relevance of an overall optimisation is again in question. There rarely is a single decision maker who has authority over a country's entire energy system, or even over only the complete fuel supply system for electricity generation. Therefore, the optimised solution must be viewed as providing only some indications of how the energy system could be improved, rather than providing information to a specific decision maker. However, in an overall energy system, individual preferences, rather than the objective choices indicated by a theoretical optimisation, often dominate the decisions. For example, suppose hot water can be produced only from water heaters using natural gas or electricity. Also, suppose that the hot water can be produced by natural gas water heaters for 1% less cost than with electricity and that all other impacts and costs are negligible. An optimisation model would select 100% natural gas water heaters, while actual practice would probably be closer to a 50-50 split (i.e. the difference in price is too small to be a major decision variable for most individuals), with a corresponding major difference in implications for the energy system.

Given the complications and limitations outlined above, there are few claims of optimisation models that address simultaneously economic, social, health and environmental implications of alternative electricity supply systems. However, some models do include a select few impacts directly in the optimisation. Such models can be used to examine alternatives that might not be recognised by using more traditional approaches. Results from such analyses should make clear the value trade-offs that are incorporated.

4.7.4. Step-by-step approach

The step-by-step approach also has many variations but typically involves a separation between the cost analysis and the trade-off analysis that addresses the environmental, health and social impacts. An advantage of the step-by-step approach compared to the optimisation approach is that the analysts are required to develop a better understanding of the key assumptions behind each step in the analysis. A disadvantage of the step-by-step approach is that it may involve the use of a set of models, rather than a single model, and thereby may require more time to arrive at the alternative evaluation stage.

The complications introduced by the need to first identify, and then quantify and evaluate, a diverse set of impacts justifies serious effort on the valuation side of the problem. Historically, the valuation side often has had only brief attention at the end of the study or very limited effort to quantify and include a limited set of impacts. In recent years, more attention has been given to the valuation side of the problem, as the importance of factors other than conventional costs have increased [56]. Three basic stages in a serious effort to include diverse factors from the beginning of a study are [59]:

- *Problem formulation.* Ingredients include: specification of objectives; estimation of resource (data, time and manpower) requirements and availability; and identification of alternatives (e.g. emphasising domestic fuel use or allowing imported fuel use).
- *Objective hierarchy selection.* This stage includes identification of specific objectives and criteria of achievement.
- *Alternatives evaluation.* This stage includes measurement of the performance of each alternative with respect to the criteria previously identified; this generally requires a model of the electric generating system, e.g. to calculate sulphur dioxide emissions each year. This also is the stage at which value judgements for different levels of achievement with respect to each criteria can be assessed and included in the analysis.

Many variations of the step-by-step approach exist. There are accepted methods for conducting such analyses, and users are advised to consult relevant publications for guidance (e.g. [60]. A general methodology for analysing alternative expansion strategies can be broken down into five steps [61]:

Step 1: Specify objectives and measures,

Step 2: Identify candidate expansion strategies,

Step 3: Describe possible impacts for each strategy,

Step 4: Evaluate site impacts, and

Step 5: Analyse and compare alternative strategies.

Some features that complicate the electric system expansion problem include:

- Numerous possible expansion strategies (e.g. coal emphasis, hydro emphasis),
- Multiple conflicting objectives (e.g. minimise cost, minimise air pollution),
- Several interest groups (e.g. electric utility, regulators, environmental groups),
- Intangibles (e.g. psychological considerations associated with nuclear power),
- Degree of impact (e.g. a scale is needed for measurement of impacts),
- Long time horizons (e.g. value of an impact may depend on when it occurs),
- Uncertainties about impacts (e.g. limited data for some effects or events),
- Operating reliability (e.g. some strategies provide more reliable electric service),
- Value trade-offs (e.g. needed to compare the set of non-dominated alternatives),
- Risk attitudes (e.g. attitudes of decision makers toward risk is important).

These features make the evaluation and comparison of alternative expansion strategies complex. The integrated analysis must address these concerns and provide measures of how alternative expansion strategies perform with respect to each objective. In addition, the electric system expansion problem has the following characteristics that provide motivation for formal analysis [61]:

- *High stakes.* The electric generating system typically accounts for a significant share of a developing country's investment spending.
- *Complicated structure.* The features listed above clearly demonstrate the complexity involved in electric system expansion planning. In addition, the models used to simulate the electric system operation, such as described in Sec. 4.4, are complex even when cost is the only variable being considered.
- *No overall expert.* Because of the many concerns affecting electric system development, no individual is an expert in all areas of concern.
- *Need to justify decisions.* Expansion plans proposed by utilities are reviewed by many different IAPs, including regulators and members of the public. Therefore, a rational approach to compare and evaluate alternatives is needed in order to justify the proposed decisions.

Thus, the trend towards more emphasis on external costs and methods for evaluating strategies over several criteria seems justified. With the features of the valuation problem as listed above, it is important to address these issues in a logical, defensible and understandable way. This often means that a separate, explicit and non-negligible effort is needed for the stage at which alternatives are evaluated.

REFERENCES TO CHAPTER 4

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electrical Generating Systems: A Guidebook, Technical Reports Series No. 241, STI/DOC/10/241, Vienna (1984).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Health Impacts of Different Sources of Energy, Proc. of Int. Symp. (Nashville, 22-26 June 1981), IAEA Proceedings Series, STI/PUB/594, Vienna (1982).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Risks and Benefits of Energy Systems, Proc. Int. Symp. (Jülich, Germany, 9-13 April 1984), IAEA Proceedings Series, STI/PUB/668, Vienna (1984).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Electricity and the Environment, Proc. Int. Symp. (Helsinki, 13-17 May 1991), IAEA Proceedings Series, STI/PUB/877, Vienna (1991).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making, Proc. Int. Symp. (Vienna, 16-19 October 1995), STI/PUB/975, Vienna (1996).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Senior Expert Symposium on Electricity and the Environment: Key Issues Papers, STI/PUB/899, Vienna (1991).

[7] CODONI, R., PARK, H. AND RAMANI, K. (Ed.), Integrated Energy Planning: A Manual, Asia and Pacific Development Centre, Kuala Lumpur (1985).

[8] DE ALMEIDA, A.T., ROSENFELD, A.H., ROTURIER, J. AND NORGARD, J. (Eds.) Integrated Electricity Resource Planning, Kluwer Academic Publishers, Dordrecht, The Netherlands (1994).

[9] KEENEY, R., Value-Focused Thinking: A Path to Creative Decision Making, Harvard University Press, Cambridge, MA, USA (1992).

[10] ONTARIO HYDRO COMPANY, Providing the Balance of Power, Demand/Supply Plan Report, Toronto (1989).

[11] SRC INTERNATIONAL APS, Integrated Resource Planning: Methodology and Models, SRC Paper No. 906-241, Hellerup, Denmark (1992).

[12] WORLD BANK, Incorporating Risk and Uncertainty in Power System Planning, Industry and Energy Department Working Paper, Energy Series Paper No. 17, Washington, D.C. (1989).

[13] TENNESSEE VALLEY AUTHORITY, Energy Vision 2020 - An Integrated Resource Plan and Programmatic Environmental Impact Statement, Chattanooga (1995).

[14] CINCINNATI GAS AND ELECTRIC COMPANY, 1992 Electric Long-term Forecast Report, Cincinnati (1992).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical Reports Series No. 245, STI/DOC/10/245, Vienna (1985)

[16] UNION INTERNATIONAL DES PRODUCTEURS ET DISTRIBUTEURS D’ENERGIE ELECTRIQUE, Least-Cost Planning in the Electricity Supply Industry: Experiences in United States and in Europe, Paris (1992).

[17] UNION INTERNATIONAL DES PRODUCTEURS ET DISTRIBUTEURS D’ENERGIE ELECTRIQUE, Integrated Resource Planning and Demand Side Management, Executive Report, Paris (1994).

[18] INTERNATIONAL CONFERENCE ON LARGE HIGH VOLTAGE ELECTRIC SYSTEMS (CIGRE), Relationship Between Power System Planning and Factors Affecting the Electricity Demand (IRP/LCP/DSM), (Proc. Int. Conf.), Report 37.93(WG11)06(E), Johannesburg (1993).

[19] RABL, V.A., “Demand-Side Management in the U.S.: Do We Have All the Answers?”, in Integrated Resource Planning (de Almeida, A.T., Rosenfeld, A.H., Roturier, J. and Norgard J., Ed., Kluwer Academic Publishers, Dordrecht, Netherlands (1994).

[20] GOLVANO, E., “The Main Problem for DSM Options Analysis: The Need for Valuable Data”, in Integrated Resource Planning (de Almeida, A.T., Rosenfeld, A.H., Roturier, J. and Norgard, J., Ed.), Kluwer Academic Publishers, Dordrecht, Netherlands (1994).

[21] CALIFORNIA PUBLIC UTILITIES COMMISSION AND CALIFORNIA ENERGY COMMISSION, Standard Practice Manual: Economic Analysis of Demand-Side Management Programs, Sacramento, CA (1987).

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Wien Automatic System Planning (WASP) Package: A Computer Code for Power Generation System Expansion Planning, Version WASP-III-Plus User’s Manual, Computer Manual Series No. 8, Vienna (1995).

[23] FAZEKAS, A., “Some design aspects considered in the elaboration of the power system expansion strategy of Hungary”, in Recent Experience in the Use of IAEA Planning Models Among the Member States of Europe, Middle East and North Africa (Proc. Int. Workshop, Budapest, 18-22 July 1994), pp. 134-144, Vienna (1996).

[24] INTERNATIONAL ATOMIC ENERGY AGENCY, The DECADES Project - Outline and General Overview, DECADES Project Document No. 1, Vienna (1995).

[25] CAMPO, R., ANGEL, E., GOMEZ, D. AND LEON, O.L., “Assessment of Environmental Issues Using SUPER/OLADE/BID for Comparing Alternative Electricity System Expansion Strategies: A Case Study for Colombia”, in Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making (Proc. Int. Symp., Vienna, 16-19 October 1995), pp. 467-473, STI/PUB/975, IAEA, Vienna (1996).

[26] BENDERS, J.F., “Partitioning Procedures for Solving Mixed Variables Programming Problems”, Numerische Mathematik, Vol. 4, pp. 238-252, Springer Verlag, Berlin (1962).

[27] WORLD BANK, ENVIRONMENT DEPARTMENT, Environmental Assessment Sourcebook, World Bank Technical Paper Number 139, Washington, D.C. (1991).

[28] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 1992 (Supplementary Report to the IPCC Scientific Assessment), Cambridge University Press, Cambridge, UK (1992).

[29] UNITED KINGDOM DEPARTMENT OF ENERGY, Report of UK Climate Change Impact Review Group, UKCCIRG, DOE, HMSO, London (1991).

[30] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change: the IPCC Impacts Assessment, Australian Government Publishing Service, Canberra (1990).

[31] PARRY, M., Climate Change and World Agriculture, UNEP/IIASA, Earthscan Publications Ltd., London (1990).

[32] KRAUSE, F., BACH, W. AND KOONEY, J., Energy Policy in the Greenhouse, IPSEP, Earthscan Publications Ltd., London (1991).

[33] PEARCE, D.W., ET AL., Blue Print 2: Greening the World Economy, Earthscan Publications Ltd., London (1991).

[34] CENTRE OF SOCIAL AND ECONOMIC RESEARCH ON THE GLOBAL ENVIRONMENT (CSERGE), The Social Cost of Fuel Cycles, Report to DTI, HMSO, London (September 1992).

[35] OFFICE OF TECHNOLOGY ASSESSMENT, Changing by Degrees: Steps to Reduce Greenhouse Gases, U.S. Congress Office of Technology Assessment, Cutter Information Corp., Arlington, VA, USA (1991).

[36] UNITED KINGDOM DEPARTMENT OF ENERGY, Acid Rain Critical and Target Loads Map for the UK, Creative Press, Reading (1991).

[37] KLAASSEN, G., AMANN, M. AND SCHOPP, W., Strategies for Reducing Sulphur Dioxide Emissions in Europe Based on Critical Sulphur Deposition Values, International Institute for Applied Systems Analysis (IIASA), Background Paper prepared for United Nations Economic Commission for Europe Task Force on Integrated Assessment Modelling, UNECE, Geneva (December 1992).

[38] INTERNATIONAL ENERGY AGENCY, Energy and the Environment: Policy Overview, OECD, Paris (1989).

[39] WILSON, R., “Some Transboundary Environmental Issues of Public Concern”, in Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making (Proc. Int. Symp., Vienna, 16-19 October 1995), pp. 387-401, STI/PUB/975, IAEA, Vienna (1996).

[40] WILSON, R. AND SPENGLER J. (Eds.), Particles in Our Air: Concentrations and Health Effects, Harvard University Press, Cambridge, MA, USA (1996)

[41] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Report No. 60, Annals of the ICRP, Pergammon Press, UK (1991).

[42] UNITED KINGDOM NATIONAL RADIOLOGICAL PROTECTION BOARD, Radiation Exposure of the UK Population - 1993 Review, NRPB-R263, London (September 1993).

[43] MASON, C.F., Biological Aspects of Freshwater Pollution: Causes, Effects and Control, Royal Society of Chemistry, Cambridge University Press, Cambridge, UK (1990).

[44] HOHMEYER, O., Social Costs of Energy Consumption, Springer Verlag, Berlin (1988).

[45] ELECTRIC POWER RESEARCH INSTITUTE, Environmental Externalities: An Overview of Theory and Practice, Report EPRI-CU/EN-7294, Palo Alto, CA (1991).

[46] HERZ, H., “External Costs of Rational Use of Energy”, in Proc. of 2nd International Conference on External Costs of Electric Power, Racine, Wisconsin (September 1992).

[47] WIEL. S., “Why Utilities Should Incorporate Externalities”, in Proc. of 2nd International Conference on External Costs of Electric Power, Wisconsin (September 1992).

[48] FREEMAN, A.M., BURTAW, D., HARRINGTON, W. and KRUPNICK, A.J., Weighting Environmental Externalities: How to do it Right, The Electricity Journal, Vol. 5, No. 7, pp 18-25 (August/September 1992).

[49] KRUPNIK, A.J., The Environmental Costs of Electricity: A Methodology Critique, Resources For The Future, Washington, D.C. (March 1991).

[50] PEARCE, D.W. AND MARKANDYA, A., Environmental Policy Benefits: Monetary Valuation, OECD, Paris (1989).

[51] MARKANDYA, A., Externalities of Fuel Cycles ‘EXTERNE’ Project, European Commission DG-XII, Report No. 9 (Economic Valuation), prepared by Metroeconomica EC/DG-XII, Luxembourg (1995).

[52] HAMALAINEN, R.P., “A Decision Aid in the Public Debate on Nuclear Power”, European Journal of Operational Research 48, pp 66-76, North-Holland (1990).

[53] POYHONEN, M., Evaluation of Environmental Policy Strategies with Imprecise Preference Information, IIASA Report WP-94-87, International Institute for Applied Systems Analysis, Laxenburg, Austria (1994).

[54] MARRIAGE, E. AND ROGERS, M., “How Generation Choices Are Influenced By Costs, Risks, and Externalities: The Generation Planning Process in Ontario, Canada”, in Power Generation Choices: Costs, Risks, and Externalities (Proc. Int. Symp.), OECD, Paris (1994).

[55] CARLE, R. AND MOYNET, G., “Power Generation Choices: An International Perspective on Costs, Risks, and Externalities”, in Power Generation Choices: Costs, Risks, and Externalities (Proc. Int. Symp.), OECD, Paris (1994).

[56] STRAUSS, L., “Generation Choices As Influenced By Costs, Risks and Externalities - Germany”, in Power Generation Choices: Costs, Risks, and Externalities (Proc. Int. Symp.), OECD, Paris (1994).

[57] MEIER, P. AND MUNASINGHE, M., Incorporating Environmental Concerns into Power Sector Decsion Making: A Case Study of Sri Lanka, Environment Department Paper Number 6, World Bank, Washington, D.C. (1994).

[58] ALBOUY, Y. AND SYSTEMS EUROPE CONSULTANTS (BELGIUM), Assessment of Electric Power System Planning Models, Energy Department Paper No. 20, World Bank, Washington, D.C. (1985).

[59] BUEHRING, W., WHITFIELD, R. AND WOLSKO, T., Methodology for Evaluation of Intertechnology Tradeoffs, Report ANL/AA-22, Argonne National Laboratory, Argonne, IL, USA (1980).

[60] KEENEY, R. AND RAIFFA, H., Decisions With Multiple Objectives: Preferences and Value Tradeoffs, John Wiley and Sons, New York (1976).

[61] KEENEY, R., Siting Energy Facilities, Academic Press, New York (1980).

CHAPTER 5

FROM ANALYSIS TO DECISION AND BEYOND

5.1. From analysis to decision

This chapter first discusses the decision making process, then examines the nature of risks and uncertainties and various techniques to deal with them in the analysis of power systems. An overview of qualitative and quantitative methods for taking into account social preferences follows. The chapter concludes with a discussion of the presentation of results from the analyses and of institutional arrangements for implementing and monitoring the programme on an ongoing basis.

5.1.1. The participatory decision making process

As discussed in Chapter 3, decisions may be taken ultimately by a formal group of decision makers, and there is increasingly an interaction between the three principal groups (analysts, IAPs and decision makers) as depicted in Figure 3.1 in Chapter 3. Rather than a single decision maker, there is typically a formal decision making body within the power sector or at a senior government level which acts upon the advice of planners from the power utility and/or government. While the interaction between the planners and decision makers has been long-standing, there is a growing interaction with the IAPs in their role as electricity consumers, tax payers or populations affected by the construction of power projects. Throughout the planning process, IAPs may be assisted by local and/or international non-governmental organisations (NGOs), particularly in connection with environmental and social issues. The strength of the interaction will vary considerably, depending on the country and the significance of the decisions to be taken.

The interaction between power sector planners and decision makers normally is well established, with clear procedures as to their respective roles and responsibilities. Decision makers establish the terms of reference for planning and give a mandate to the planners to prepare a plan and make recommendations. The planners carry out the analysis, then present and defend their conclusions and recommendations, possibly with several iterations in the process. The extent to which the IAPs are involved will depend on the form of government, the degree of democracy and the degree to which IAPs have a voice and opportunity for participation in planning and decision making. Increasingly, however, governments and planners are strengthening the involvement with IAPs throughout the process. International financing institutions such as the World Bank have clear policies designed to ensure that the issues and impacts of power projects on IAPs are fully identified and dealt with in the planning process and throughout the project cycle [1].

Using participatory processes, key stakeholders identify objectives, define the constraints to changing them and develop strategies and tactics for addressing them. In so doing, stakeholders bring their knowledge and experiences to bear on the problem, and they learn and develop ‘ownership’ as solutions are worked out. For these reasons, decisions made in a participatory context generally are more feasible and sustainable than decisions made by experts alone.

Participation is particularly important when the criteria for choice do not lead unambiguously to ‘win-win’ solutions, i.e. solutions that satisfy all stakeholders. Because externalities cannot be fully assessed in monetary terms and because there is not symmetry among stakeholders with regard to costs and benefits, there often is a need to make trade-offs, typically in the area of increased investment and/or operating cost in order to address environmental and social issues that cannot be accounted for in purely monetary terms, as discussed below.

5.1.2. Win-win options and trade-offs

While all three groups (planners, decision makers and IAPs) are concerned with the outcome of the decision making process, each group has a different viewpoint and attaches different weights with regard to various issues. Multi-criteria analysis (MCA) offers policy makers an alternative when progress toward multiple objectives cannot be measured in terms of a single criterion (i.e. monetary value). It also provides decision makers with a range of feasible alternatives as opposed to one ‘best’ solution (see Figure 5.1), as normally would be obtained through the use of optimisation models.

The concepts of MCA are most apparent in the case of, for example, the introduction of an efficient fuelwood stove, although they are equally applicable to power development strategies (adapted from [2]). As shown in Figure 5.1, outward movements along the axes trace improvements in three indicators: economic efficiency (e.g. net monetary benefits), social equity (e.g. improved health), and environmental pollution (e.g. reduced deforestation). Policy options are addressed as follows. First, triangle ABC describes the existing fuelwood stove, for which economic efficiency is moderate, social equity is low, and overall environmental impact is high. Next, triangle DEF indicates a 'win-win' future option in which all three indices are improved, as could occur with an improved fuelwood stove that provides efficient energy and more benefits to the poor. The economic gains could included monetary savings from reduced fuelwood use and health benefits from reductions in acute respiratory infections, lung disease and cancer caused by pollutants in biomass smoke. Social gains would accrue from the fact that the rural poor benefit the most from this innovation - for example, owing to the reduced time spent on collecting fuelwood thereby freeing up time for more productive activities and lightening the labour burden on women and children. The improved stove also will produce environment benefits, since the more efficient combustion will lower demand for fuelwood and thereby reduce deforestation and lead to lower greenhouse gas emissions.

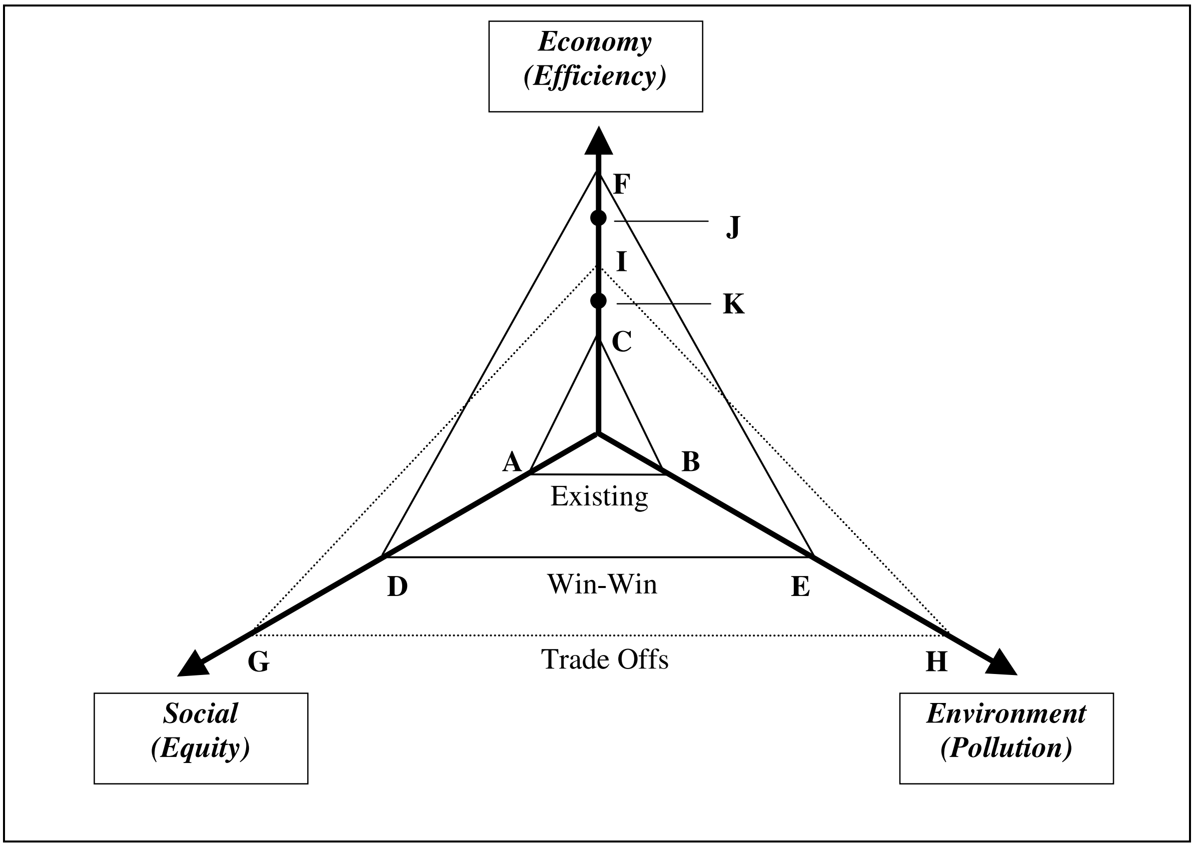


FIG. 5.1. Multi-criteria analysis of alternatives.

After realising such 'win-win' gains, other available options would require trade-offs. In triangle GHI, further environmental and social gains are attainable only at the expense of sharply increasing costs. For example, shifting from fuelwood to LPG or kerosene as a fuel may increase economic costs, while yielding further environmental and social benefits. In sharp contrast to the move from ABC to DEF, which is unambiguously desirable, a policy maker may not wish to make a further shift from DEF to GHI without knowing the relative weights that society places on the three indices. Such preference often are difficult to determine explicitly, but it is possible to narrow the options. Suppose a small economic cost, FJ, yields the full social gain DG, while a large additional economic cost, JK, is required to realise the environmental benefit EH. Here, the social gain may justify the economic sacrifice. Further, if purely budgetary constraints limit costs to less than total requirement, FK, then sufficient funds exist to pay only for the social benefits, and the environmental improvements will have to be deferred.

A power system planning study in Sri Lanka [3] demonstrated the versatility of the MCA approach. In this case, end-use energy efficiency measures provided 'win-win' options (i.e. they were superior to all other alternatives on the basis of air quality, biodiversity loss and economic cost). Conversely, several prominent hydropower projects could be excluded because they performed poorly in terms of both biodiversity loss and economic costs.

5.2. Decision making in an uncertain world

Uncertainty and risk are present with regard to many aspects of planning and decision making. *Uncertainty* means 'not know with certainty'; hence, elements with uncertainty are those upon which there is a lack of definite knowledge and which can result in the failure to achieve a sound development programme. *Risks* are the chances of harm or losses to the investor or consumer that are inherent to decisions taken within an uncertain environment. Thus, *uncertainty* refers to lack of knowledge about future events and *risk* refers to the possible adverse consequences of this uncertainty.

Power generation planning requires extensive risk analysis because of the long time horizons (i.e. planning periods for analysing the least cost expansion programme plus lead times for project implementation), the large capital investments and the uncertainty of demand [4].

While risk analysis needs to be carried out at all stages in the project cycle, the focus of analysis will vary depending on the project cycle stage. Prior to taking final decisions concerning the acceptability of a particular power expansion project, sector planners need to stand back from the analytical results and draw on global experience to assess a project's risk. In the final assessment phase, the appraiser should not repeat routinely the steps carried out during the preparation of sector plans or assessment of specific projects, but instead should follow a different approach in order to avoid the incorporating the same biases which might have been present in the initial analysis.

The main objectives of risk analysis are to protect the interests of all parties by improving the quality of projects and to reduce the probability and consequences of 'bad decisions'. In this respect, risk analysis will help to:

- identify the sensitivity of the present value of expected net benefits to changes in key variables such as demand, capital cost and fuel prices, and the timing of the project (planned variations in project timing, as opposed to schedule slippage or early completion, constitute alternative mutually exclusive project designs);
- prepare contingency plans to protect against possible adverse outcomes;
- test the proposed project(s) for robustness against risks and in comparison with alternative designs, i.e. demonstrating that the project is least cost in comparison to alternatives, including investments in demand management and efficiency improvements;
- assess the value of keeping options open; this is important in the case of a hydro project which makes less than full use of a site and thereby precludes future development to a larger size or in the case of a single large hydro project that precludes the development of a more flexible programme of smaller projects, while keeping open the option of the larger project at a later date [5];
- assess the impact of shortfalls in investments in complementary facilities required to obtain full project benefits; e.g. additional transmission and distribution facilities likely will be needed to distribute the output of a power generation project;
- identify the critical variables to be monitored during implementation in order to assess any need for design modification;
- identify who bears the risk, including the power utility, government, private sector financiers and/or consumers.

When private investors, particularly foreign investors, are involved in sector financing, a further spectrum of risks must be considered, primarily by the investors themselves but also by the power purchaser and the government in their consideration of the cost of power. Commercial entities and private investors must consider such matters as [6]:

- the potentially large indirect costs arising from a loss of productive capacity;
- areas where private and official insurers, such as the USA Overseas Private Investment Corporation (OPIC) and the World Bank affiliated Multilateral Investment Guarantee Agency (MIGA), can protect project owners and financiers against commercial and political risks;
- gaps in normal insurance coverage that might affect a borrower's ability to repay loans.

5.2.1. Nature and impact of uncertainties

Uncertainties in key project variables, such as demand, capital cost, project completion date and fuel prices, lead to risks that the expected project costs and benefits will differ significantly from the estimated values. While some project variables — such as construction schedule (and hence, completion date) and capital and O&M costs — may be controllable, other variables or risk factors - e.g. hydrology, geology or rate of siltation of a hydro reservoir - may not be controllable. Even if not fully controllable, the impacts of adverse conditions usually can be reduced through further study and more thorough planning.

In the case of both controllable and uncontrollable risks, the variance of the estimate can be reduced or its expected value estimated with greater precision through further study. The value of further studies is, of course, subject to diminishing returns with each increment of study cost (i.e. a large investment in further studies may bring only marginal improvement in the quality of the results). Correlation among variables must be considered also in order to capture the joint impact of variables such as project cost and completion date.

Financing risks associated with revenues (tariffs and demand level), exchange rate and the availability of foreign exchange will be a major factor in securing private sector participation and ensuring long term sustainability of the power sector and its expansion programmes [6]. Any failure of the implementing agency to complete the project on schedule and/or to operate the plant effectively after commissioning will raise costs and/or lower benefits.

5.2.2. Identification and quantification of uncertainties

The success of a project in terms of realising the estimated net benefits is subject to uncertainties in both costs and benefits, most of which are quantifiable on the basis of the following variables:

(I) Costs

(i) *capital*: physical quantities and unit costs, particularly related to large civil works in hydro projects; project completion delay raises costs, particularly for interest during construction [7];

(ii) *fuel*: particularly with regard to international prices over the long term;

(iii) *operation and maintenance costs*: although these generally are not as significant as capital and fuel costs, higher levels (and costs) of O&M may, in fact, lead to increased benefits because of greater reliability of project outputs and longer plant life;

(iv) *externalities:* in terms of environmental impacts, these are difficult to quantify, as noted above, but should be taken into account if known; the impact of variations in resettlement costs (especially for large hydro projects) and emission mitigation costs (for fossil fuelled plants) on alternative expansion programs can be assessed and internalised.

(II) Benefits

- (i) *demand forecast:* project completion reports and other studies show a systematic tendency to over-estimate demand; hence, specific attention must be paid to the risk of low demand [8]. Appraisal of the demand forecast should include a validation against alternative approaches to forecasting. Since forecasts are frequently based on the aggregation of consumer classes such as industry, residential, etc., it is essential to compare this 'bottom up' approach with a 'top down' forecast taking into account GDP growth rate, trends in prices and incomes, and assumptions concerning price and income elasticities (see Chapter 4);
- (ii) *unit value of benefits:* in terms of tariffs and compensated consumer surplus measured by estimates of willingness to pay (WTP) for alternative forms of energy;
- (iii) *project output*
    - (a) project *completion delay:* results in lost output and higher cost of substitute or unserved energy (if not, the project is premature and should be deferred);
    - (b) *hydro energy production:* depends on hydrology and turbine-generator efficiency
    - (c) *project life:* before major overhaul (particularly diesel power plants) or loss of output due to siltation in hydro reservoirs;
    - (d) *reliability and availability of units:* consequence of low performance may be increased load shedding or increase in expected unserved energy, with unit costs greater than measured by the tariff;
    - (e) expected *value of investments of demand side management and energy efficiency* programs is uncertain and the variance is high due to the general inexperience with these programs.

Successful implementation of the project also depends on the availability of funds. In the event of a shortfall in funds, design revision may be required, thereby reducing project output. The risk of this outcome should be assessed as part of contingency planning.

5.2.3. Risk analysis methods and techniques

Some form of risk analysis will need to be carried out as a part of any project or expansion planning process. The complexity of the analysis will depend on the intended purpose of the plan (i.e. only indicative strategies or selection and commitment of a project) and the nature and range of the risks and uncertainties. In all cases, one must begin with a clear understanding of the inter-relationship of project components and the consequences of planned and unplanned alternative outcomes. The degree of detail and analytical sophistication that should be applied depends on the value of additional information to be gained and the significance of that information. If a project is marginal (i.e. has a low internal economic rate of return) and risky, then a more rigorous analysis is needed in order to identify adequate measures for hedging against risks. A project which has a high rate of return, despite a wide variance of costs and benefits, will need only elementary sensitivity analysis. Stages of analysis, in order of increasing rigor, are indicated below:

- (a) *Decision tree analysis* - Identification of the consequences of taking a decision which is subject to different uncertain outcomes.
- (b) *Rudimentary sensitivity analysis* - What happens if variables change by, say, 10-20%? Sensitivity analysis of project costs and schedules (and other parameters such as plant availability) should be based on variations from the base case which has been calculated using *expected values* rather than *estimated* values which are not likely to

have the same numeric values because of the skewed nature of the underlying probability distribution [6, 9].

(c) *Calculation of switching values* - What is the change in a given variable that will cause the internal economic rate of return (IERR) or net present value (NPV) to drop below the threshold value of acceptability?

(d) *Assessment of probability* that variables could change by amounts indicated in (b) and (c) above.

(e) *Formal probabilistic risk analysis* - Rigorous analysis can be carried out using spreadsheet models and Monte Carlo simulation tools; an assessment of probability distributions and degree of correlation between variables is required to obtain a complete risk assessment.

(f) *Trade-off and risk method* - This technique can be applied in power generation planning to test the trade-off between risk and different project variables [10].

(g) *Option valuation method* - This technique applies financial option valuation methods to assess the value of keeping options open as a hedging technique in the face of uncertainty [5].

Among the techniques mentioned above, items (e) and (f) can be particularly useful in gaining important insights. The Monte Carlo simulation tools can be used in conjunction with spreadsheets in order to assess quite rapidly the impact of key variables and different assumptions concerning the associated probability distributions. While they can be used effectively during the course of the planning studies, these tools can help also in the later stages of the study for preparing a synoptic assessment of, say, the probability distribution of the rate of return (ROR) and the risk that the selected ROR might be unacceptably low.

5.2.4. Trade-off and risk method

The trade-off and risk method is a more elaborate approach can be applied during the course of the power planning study, although the need to use it may be assessed through the use of a simpler spreadsheet analysis together with Monte Carlo simulation. The trade-off and risk method (see Chapter 3) is a strategic planning approach that consists of four steps:

- formulating the planning problem;
- developing a data base;
- trade-off analysis;
- risk analysis.

The least cost planning problem is formulated in terms of options, strategies and futures. *Options* include different possible measures for meeting demand (e.g. plant types, load management, electricity imports) and the attributes of those options (e.g. economic cost of electricity, quality of service, capital requirements, environmental characteristics). Strategies are formulated by assuming different possible combinations of options. *Futures* are based on different assumptions regarding the likely outcomes of uncertainties (e.g. load growth, fuel prices). A data base is created of all reasonable combinations of options, strategies and futures. The attribute values for each combination are obtained through simulation using planning models such as WASP [11], ENPEP [12] and DECADES [13]. It often is possible to perform a relatively small number of simulations and then expand the data base using a linear interpolation procedure. Trade-off analysis is necessary because it is usually impossible to optimise a plan (strategy) in terms of all objectives simultaneously. Figure 5.2, as an illustration based on a study carried out in Hungary [14], shows that: plans that require high capital cost may have low total cost; and, conversely, some of the plans that require the lowest capital cost may lead to high total cost. In this situation, the plans that are remote from the trade-off curve should be avoided, because they can be improved upon in terms of both capital and total cost, by selecting a plan on or near the curve. The most interesting plans (denoted by round points) are close to the ‘knee’ of the curve. The trade-off and risk method includes tools for identifying trade-off curves and their knees.

Risk analysis is an iterative procedure within the larger trade-off process. It is done in four steps:

- perform trade-off analysis for each combination (futures) of possible outcomes of the uncertainties and develop a short list of plans;
- evaluate the robustness of each plan in the short list;
- if no plan is completely robust, estimate the risk exposure of each plan;
- develop contingency plans as hedges to protect against adverse futures.

The Hungary case study, for example, revealed significant conflicts in objectives, but showed the possibility of acceptable compromise plans at the knee of a multi-attribute trade-off surface (Figure 5.2). It was found that there was a fundamental conflict between the ‘minimise new investment’ objective and the other objectives that reflect the cost of electricity, SO_2 emissions, system reliability and oil consumption. A significant conclusion was that attractive solutions in terms of the other objectives were possible when capital availability was not a constraint. This conclusion is of particular importance to developing countries, since their capital requirements for power supply expansion are huge, thus indicating the need to seek new ways of mobilising financial resources and the adoption of policies to encourage more efficient production and end use of power.

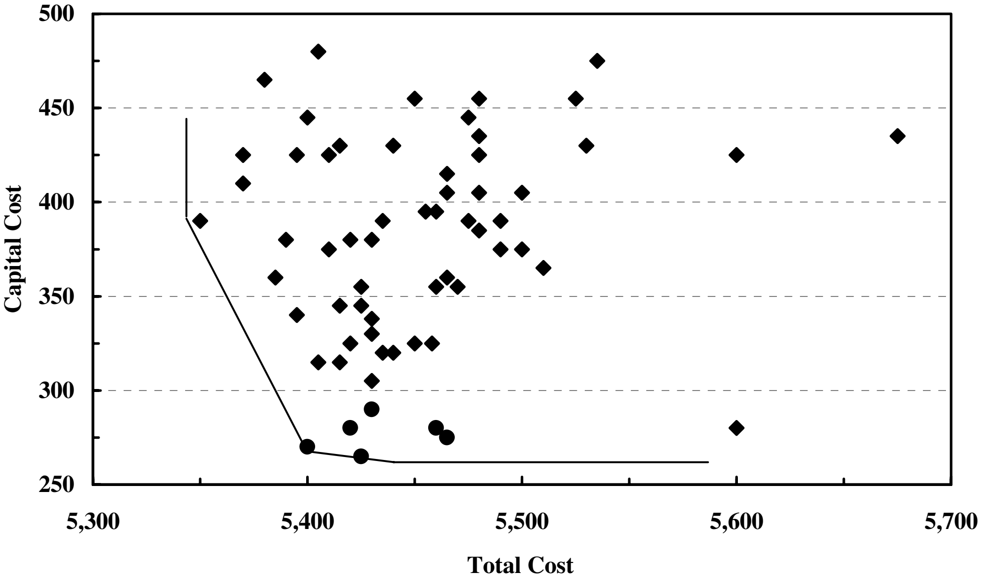


FIG. 5.2. Example of trade-off between capital and total cost.

5.2.5. Contingency planning and hedging against risk

Greater subdivision of a project (i.e. a larger number of smaller units) will increase the flexibility to respond to changing outcomes (e.g. load growth being slower than expected). In particular large hydro or thermal projects, which are monolithic and must be completed essentially as designed in order to provide benefits, can present significant risks. Breaking a large project into a series of smaller stages may be the preferred alternative in order to provide a hedge against risk, even if the revised project would have a higher present value of cost.

In power generation, risks can be reduced through partial redundancy of system components, for example through the installation of two smaller generating units instead of one large unit or through the provision of two tunnels for carrying water to a hydropower turbine as a hedge against loss of the entire capacity due to failure or outage of a single tunnel. The option of dual firing for fossil fuel boilers provides a hedge against fuel price increases and/or fuel supply interruptions. In these cases, there may be a loss of economies of scale, but such losses may be off-set by economic gains through increase in reliability and reduction in risk.

During project implementation, monitoring indicators need to be tracked so that steps can be taken to improve project management or revise the project through the implementation of hedging plans according to pre-identified criteria as outlined above. Key indicators will include project costs and schedule as well as the overall level of sector demand for, say, electricity or gas.

The type of risk analysis which needs to be carried out depends in part on the stage in the project cycle. At the project identification and preparation stages, feasibility studies should (and typically do) examine alternative designs according to base case (expected) and high or low demand scenarios. The recommended alternative should be subjected to a full assessment of risk factors, using formal risk analysis procedures as necessary. Likewise, a sensitivity analysis should identify key variables to monitor during implementation. Finally, contingency plans should be prepared which anticipate possible revisions in project design as hedge against risks.

Contingency and risk mitigation plans for managing risks in order to avoid unacceptably low project returns can be prepared through a process involving the following steps:

(1) establish a risk list based on a 'brain-storming' session among technical, economic and financial specialists with experience in similar projects;

(2) establish a list of possible risk mitigation strategies that would address the risks identified in (1);

(3) model the stochastic nature of project implementation without the risk mitigation strategies, in order to determine the expected rate of return and its probability distribution;

(4) analyse the impact of each of the risk mitigation strategies in order to determine their impact on expected returns and its variance;

(5) formulate a recommended risk mitigation strategy based on the analysis in (4).

5.3. Presentation of the recommended power system expansion programme

5.3.1. Presentation to decision makers

The normal vehicle for presenting the results of a planning study is a voluminous report with numerous technical appendices supporting the analytical work and conclusions. Such reports are essential to documenting the work and providing the basis for a thorough review. Decision makers, however, cannot be expected to absorb the large amount of material and follow all the details presented. They will, of course, want to be satisfied that the reports have been soundly prepared and thoroughly reviewed in regard to the nature of assumptions, appropriateness of methodologies, quality of work, and validity of conclusions. Their primary concern as decision makers will be to see the recommendations in the broader context of the power and energy sectors and the macro-economy. It is essential that a summary report, prepared for the decision makers, presents the recommendations in this context. Decision makers must see clearly that the expansion programme and specific projects are technically feasible, economically justified and can be financed. The conformity of projects with government policies, and with those of international financing agencies if these sources will be used for funding, also must be apparent.

The hardest task often is preparing the summary report and the presentation to be given to decision makers. Very often, it is difficult for the principal authors of the main report to prepare the final summary and recommendations, because of the tendency of analysts to lose perspective after working for a long period on the studies. This problem can be overcome by bringing in new team members to take the lead, or at least assist, with the final work. Having a fresh perspective, the new members can ask the tough questions (and help prepare the answers to them) that are likely to be asked of the team upon presentation to decision makers and the public at large.

While it may appear obvious, the presentation of the recommendations must respond clearly to the basic questions:

- what are the needs for electricity?
- does the recommended power expansion programme meet those needs at lowest cost?
- does it meet environmental and other criteria?
- what are the alternatives?
- what are the risks and how will they be managed?

5.3.2. Public involvement in decision making

Public involvement in planning and implementing projects can be brought about through consultation and participation. The key factor that distinguishes consultation from participation is the degree to which those involved are allowed to influence, share or control decision making. Consultation is important during the planning phase, when strategic options remain open and before positions become hardened on options that might ultimately be included or excluded from an investment programme or as near-term projects. Under certain conditions, participation is essential during project preparation and is generally recommended as part of implementation. Information dissemination is a necessary precondition for consultation and participation (see Annexes VI and VII).

The information should be provided in a timely manner and in a form that is meaningful for, and accessible to, the groups involved. For the first round of consultations, in the resource identification phase of sector analysis and planning, the information normally includes a summary of the project description and objectives, and the potential negative impacts from the proposed project. At the stage of presentation and review of the recommended power expansion programme, a summary report as described above, together with access to the supporting materials, must be made available to all IAPs well in advance of the scheduled consultations.

Consultation involves soliciting people’s views on proposed actions and engaging them in a dialogue. Unlike information dissemination, consultation is characterised by two-way information flow, from project authorities to IAPs and vice versa. While decision making authority is retained by governments, interaction and feedback allows IAPs to influence the decision making process by raising issues that should be considered throughout the phases concerned with planning, analysis of alternatives, implementation and monitoring.

5.4. Beyond decision making: Implementation, evaluation and monitoring

Decision to proceed with a project or sector development programme is the culmination of the preparation phase of the normal project cycle. It is only a milestone, since the project must then be implemented through the process of letting contracts, construction and commissioning of plant and equipment. This process is well established in countries with large power development programs, and therefore is not discussed in this book.

The implementation of environmental management plans within projects can be more difficult, because of the greater uncertainties associated with, say, resettlement of populations to make space available for large hydro or thermal power projects. In this area, community based organisations and NGOs can have a large effect, either supporting or opposing, at the project implementation stage.

5.4.1. Environmental management plans

Environmental management plans (EMPs) outline the measures to be taken during project implementation and operation in order to control adverse environmental impacts and the actions that may be needed to implement those measures. Such plans are essential for most large and complex power projects, while a mitigation plan may suffice for simpler projects. An environmental management or mitigation plan should include the following items:

- Identification and summary of all anticipated adverse environmental impacts;
- Description of each mitigation measure, including the type of impact to which it relates and the conditions under which it is required (e.g. continuously or only in the event of contingencies), together with designs, equipment descriptions and operating procedures as appropriate;
- Institutional arrangements (i.e. who is responsible for mitigation measures);
- Implementation schedule for environmental protection measures that must be carried out as part of the project, showing links with overall project implementation plans;
- Monitoring and reporting procedures that are designed to ensure early detection of conditions that necessitate special mitigation measures, and to provide information on the progress and effectiveness of mitigation; and
- Cost estimates and sources of funds for both the initial investment and the recurring expenses for implementing the environmental management or mitigation plan, as a integral part of the total project costs.

5.4.2. Monitoring the effects and measuring compliance

During the implementation of an environmental action or resettlement plan, NGOs can act in various capacities including as project contractor or manager for the delivery of services, construction, etc., promoter of community participation, financial intermediary, supplier of technical knowledge and information and as advisor to local beneficiaries, among other roles. As part of the project monitoring and evaluation activities, NGOs can be contracted to monitor project progress or to evaluate project results and facilitate participation in this work. Most importantly, NGOs can help to provide independent monitoring and evaluation of the mitigation programme, which may be more objective (or be so perceived by the public) than would be monitoring and evaluation carried out by the implementing agency.

Two types of monitoring may be specified within an EMP. *Compliance monitoring* deals with verifying that agreed measures have been implemented. During the construction phase for example, it may involve checking the performance of contractors or government institutions against commitments expressed in formal documents, such as contract specifications or loan agreements. During the post-construction phase, it may involve measuring physical, biological or social parameters against required standards (e.g. measuring air and water discharges against national or other standards.)

In contrast, *effects monitoring* is concerned with what happens to the physical, biological or social environment as construction proceeds and beyond. This may involve validating the predictions of impacts made in the Environment Impact Assessment (EIA), verifying that mitigation measures work as planned or detecting unexpected impacts.

It is important to strike a balance between the two types of monitoring. For a project with well defined environmental impacts that can be mitigated with proven measures, it may be sufficient to rely primarily upon compliance monitoring to verify that mitigation measures are being taken. Conversely, as the degree of uncertainty in prediction of impacts and the effectiveness of mitigation measures increases, effects monitoring becomes more critical. This might be the case, for example, for discharge of an effluent into a stream from, say, an ash settling pond, where relationships between pollution concentrations and the survival of aquatic species are not well understood. This situation may necessitate monitoring of the effluent to ensure that applicable standards are maintained, as well as monitoring species populations to determine any detrimental effects. Where such uncertainties exist, there should be established agreements with regard to appropriate corrective actions that would be undertaken in case monitoring indicates a violation of pre-agreed limits.

5.4.3. Project completion reports

Upon completion of a project, a project completion report (PCR) is prepared and may be followed by a project audit carried out by financing institutions, government agencies or independent organisations having responsibility for such audits. The PCR should include a description of the impacts that actually occurred, a determination as to whether or not they were anticipated in the EIA report (if one was required), and evaluation of the effectiveness of mitigating measures and of institutional strengthening and training. Additional items useful in evaluating the environmental aspects of the project include:

- discussion of the extent to which recommendations of the EIA were followed;
- an assessment of the influence of the EIA on decision making regarding project selection and implementation;
- identification of problem areas to be considered in future environmental work;
- assessment of project operation and maintenance and their effect on the performance of pollution control equipment, compliance with emission limits, etc.;
- evaluation of costs and benefits of the environmental components of the project.

5.5. Concluding remarks

This reference book has discussed the rationale, and described an overall process, for integrating technical, economic, health and environmental factors into power sector planning and decision making. The process described has intentionally focused on setting out systematic planning methodologies based primarily on the evaluation of technical and economic data. There is, however, an implicit assumption in this process that once decisions are taken, everything goes according to plan.

The real world unfortunately does not behave so neatly. There are many risks and uncertainties which impinge on the eventual outcome of decisions and the performance of the power systems that are subsequently constructed. These outcomes can arise from a less than complete understanding of the impacts of power system development on the environment, since knowledge concerning the behaviour of environmental systems is more limited than for the physical systems of power generation, transmission and end-use. At the same time, a number of variables - such as demand, hydrology (affecting hydro generation) and the performance of power plants - are stochastic, and the combined result of their interaction can be realistically forecast only within an uncertain range and subject to a probability distribution. The more sophisticated of the planning models described in previous chapters do take such factors into account; however, it is important to make an independent assessment of these and other risks as the basis for preparing a risk mitigation plan.

Decisions concerning power development need to take into account the social preferences of the populations who not only enjoy the benefits of power development but also pay the costs both directly and indirectly. As nations become more democratic, governments, which previously had been the primary decision makers for power development, are increasingly consulting with IAPs. Since the needs for power at the least cost can conflict with social and environmental goals, decision makers will want to understand the nature of the trade-offs which must be made in the short term and in the long run.

Power sector planners not only need to make assessments of risks and social preferences, but at the same time they need to understand the process of how decisions will be taken, who influences that process, and what are the concerns of each of group involved.

REFERENCES TO CHAPTER 5

[1] WORLD BANK, World Bank Operational Directive OD4.01, Environmental Assessment, Operations Policy Department, Operations Directive (OD) Series, Washington, D.C. (1998).

[2] MUNASINGHE, M., Sustainable Energy Development (SED): Issues and Policy, Environment Department, World Bank, Washington, D.C. (February 1995).

[3] MEIER, P. AND MUNASINGHE, M., Incorporating Environmental Concerns into Power Sector Decision Making: A Case Study of Sri Lanka, Environment Department Paper No. 6, World Bank, Washington, D.C. (1994).

[4] WORLD BANK, Incorporating Risk and Uncertainty in Power System Planning, IEN Energy Series Paper No. 17, Washington, D.C. (June 1989).

[5] WORLD BANK, Decision Making Under Uncertainty - An Option Valuation Approach to Power Planning, IEN Energy Series Paper No. 39, Washington, D.C. (August 1991).

[6] WORLD BANK, Managing Risks of Investments in Developing Countries; IEN Energy Series Paper Number 55, Washington, D.C. (May 1992).

[7] WORLD BANK, Understanding the Costs and Schedules of World Bank Supported Hydroelectric Projects, IEN Energy Series Paper No. 31, Washington, D.C. (July 1990).

[8] WORLD BANK, Review and Evaluation of Historic Electricity Forecasting Experience (1965-1985), IEN Energy Series Paper No. 18, Washington, D.C. (June 1989).

[9] WORLD BANK, Factors Associated with the Reliability of Cost and Schedule Estimates for Power Generation Projects in Developing Countries, IEN Technical Series Paper, Washington, D.C. (in publication).

[10] WORLD BANK, The Trade-Off/Risk Method: A Strategic Approach to Power Planning, IEN Energy Series Paper No. 54, Washington, D.C. (May 1992).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Wien Automatic System Planning (WASP) Package: A Computer Code for Power Generation System Expansion Planning, Version WASP-III-Plus User's Manual, Computer Manual Series No. 8, Vienna (1995).

[12] HAMILTON, B., ET AL., Energy and Power Evaluation Program (ENPEP): Documentation and User's Manual, Report ANL/EES-TM-317 Rev. 1 (September 1994), Argonne National Laboratory, Chicago (1994).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, The DECADES Project - Outline and General Overview, DECADES Project Document No. 1, Vienna (1995).

[14] CROUSILLAT, E.O., DÖRFNER, P., ALVARADO, P. AND MERRILL, H.M., Conflicting Objectives and Risk in Power System Planning, IEEE Transactions on Power Systems, vol. 8, No. 3 (August 1993).

ANNEX I

SUMMARY OF COMPUTER TOOLS

Within the DECADES Project, a working document on “Computer tools for comparative assessment of electricity generation options and strategies” was prepared by the IAEA. The document included information about different computer tools, based on descriptive information provided by the individuals or institutes responsible for the maintenance and distribution of those tools. The document highlighted the objectives of those tools, their main capabilities, and some limitations to their use in decision support studies for the electric power sector.

This Annex presents a summary of the information contained in the above mentioned working document, in order to provide the reader with background information on the main characteristics and capabilities of a number of selected computer tools for comparative assessment of electricity generation options and strategies. The criteria used for selecting the tools presented in this Annex include:

- The tools should be able to address the main elements of comparative assessment of different electricity generation options, in particular in terms of their economic and environmental characteristics;
- They should be available at low or no cost;
- They should run on Personal Computers (PCs).

Since the scope and the time frame of the work for preparing the above mentioned working document did not permit any testing of the tools, the material was collected mainly through a questionnaire sent to the developers of various models and computer tools. For more detailed information, the reader is invited to contact the persons and organisations responsible for the development and dissemination of their respective computer tools (see Table I.2).

For purposes of presentation, the tools have been sub-divided into four categories: energy information systems; energy system models; modular packages; and, integrated models. The differences among these categories are highlighted below.

Energy information systems usually contain only a database and some means to analyse the data. Such tools generally are less comprehensive in scope than energy models. A simplified diagram of an energy information system is shown in Figure I.1.

Energy system models are used to analyse energy supply systems, although some of them are extended to include parts of the energy demand analysis. Others provide additional features for estimating socio-economic and environmental impacts associated with the energy systems. A simplified diagram of an energy system model is shown in Figure I.2.

Modular packages are integrated software packages for macro-economic analysis, for balancing energy supply and demand, or for estimating energy demand growth. The user does not need to run all modules of the analytical model, but may select only a subset depending on the nature of the analysis. A simplified diagram of a modular package is shown in Figure I.3.

Integrated models models are driven by an integrated set of simultaneous equations, usually covering the interactions among energy-economy-environment.

However, the comparison and classification of models is not straightforward, because most models have been designed for specific purposes and are aimed at different target audiences. The following characteristics, in particular, make an objective comparison difficult, if not impossible:

- The underlying economic structure varies from model to model;
- Some tools contain generic built-in databases for power plants and other energy chain facilities, which allows easier understanding of the data requirements - although data intensity is more a function of the analysis than a characteristic of the tool;

- It frequently is not clear how knowledgeable the user should be on computer sciences and energy systems;
- The terminology might be confusing; even developers rarely reach a consensus on the meaning of many terms.

Table I.1 summarises the key characteristics of the tools. A more comprehensive description of each model can be obtained by contacting the developer or sponsoring organisation, as listed in Table I.2.

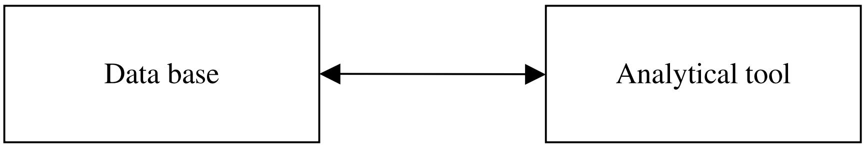


FIG. I.1. Simplified diagram of an energy information system.

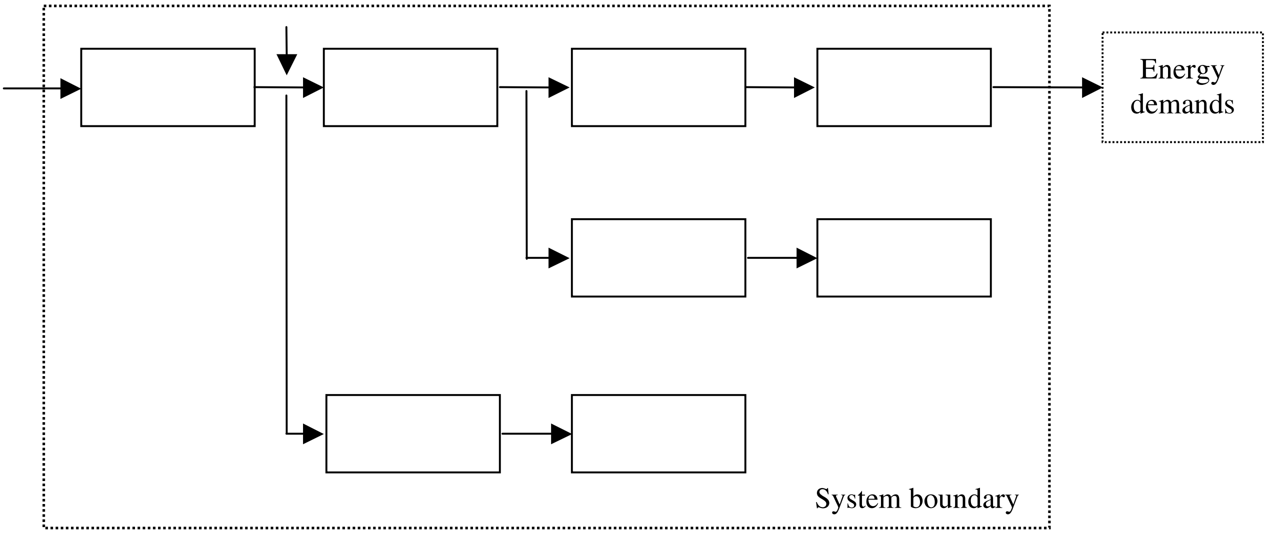


FIG. I.2. Simplified energy system model.

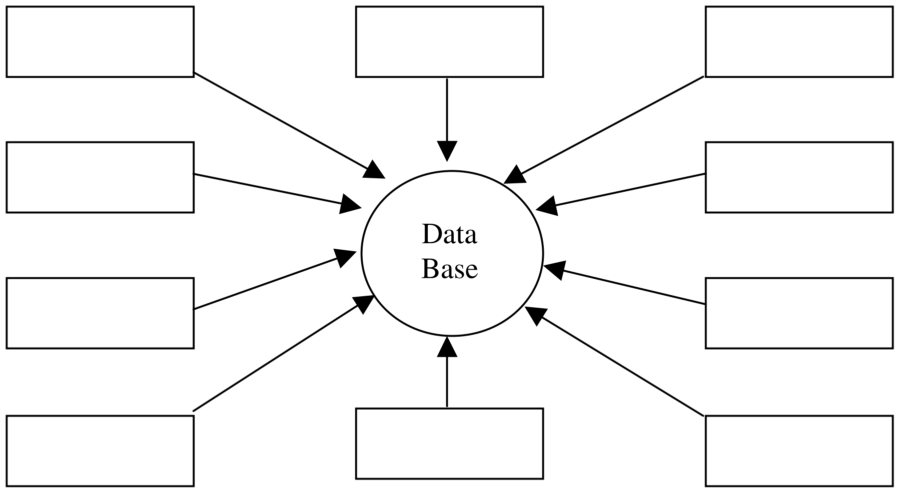


FIG. I.3. Simplified modular package.

TABLE I.1. PRINCIPAL CHARACTERISTICS OF SELECTED TOOLS FOR ENERGY AND ELECTRICITY ANALYSIS

C*	Name	Organisation (1)	Method	Data Intensiveness (2)	Scope	Extent of Use
I	CO_2DB	IIASA	Network database with comparison options	n.a.	Environment, Technology Inventory	distributed to about 50 institutes
II	EFOM	EC	Linear Programming	Medium to High	Energy System, Environment, Electricity Planning	12 EC Member States, Poland, Mexico, Dominican Republic
	MARKAL	IEA, ETSAP	Linear Programming	Medium to High	Energy System, Environment, Electricity Planning	Many IEA Member States, some 25 countries world-wide
	MESSAGE-III	IIASA	Linear Programming with econometric simulation	Medium to High	Energy System, Environment, Electricity Planning	Many countries
	ENPEP	IAEA/ANL	Simulation Model Framework, depends on module	Medium to High	Energy System, Environment, Electricity Planning	Many countries
	LEAP	TELLUS Institute	Simulation	Low	Environment, Energy System, Land Use	Many countries; mainly developing countries
III	MESAP	IER	Econometric Simulation & Linear Programming	Medium to High - depends on problem to be studied	Energy System, Environment, Electricity Analysis and Planning	Some 10 countries
	SUPER/OLADE-BID	OLADE/IDB	Least Cost Electricity Generation Expansion	Medium	Electricity Planning, Demand Side Options, Environment	Some 5-10 countries
	DECPAC/PHASE 1	IAEA	Simulation Model Framework	Low	Integrated Electricity, Economics, Environment Analysis	Some 25 countries
IV	MARKAL-MACRO	Brookhaven National Laboratory	Macroeconomic, Non-linear Optimisation	Medium to High	Integrated Economy, Energy, Environment Analysis	Some 5-10 countries
	MICRO-MELODIE	CEA	Econometric - for Energy Supply	Medium to High	Macroeconomic and Environment Aspects of Energy Policies	Some 5-10 countries
	ESG	Swiss Federal Institute of Technology	Econometric, Proportionate Allocation (converging to LP solution)	High	Energy Planning, Economy, Environment	Some 5 countries

C* Model Category: I - Energy Information System; II - Energy System Model; III - Modular Package; IV - Integrated Package

(1) Organisation to contact for further information on the tool (see Table I.2 for contact details).

(2) Estimates based upon the documentation submitted by the sponsoring organisation. n.a. = not applicable.

In the large models, data intensiveness is dependent also upon the detail the user wishes to define.

TABLE I.2. LIST OF CONTACTS FOR DETAILED INFORMATION ON THE ENERGY ANALYSIS TOOLS

Model	**Organisation**	**Contact Person**
CO_2DB	IIASA Schlossplatz 1 A-2361 Laxenburg, Austria	Nebosha Nakicenovic Tel: +43-2236-0 Fax. +43-2236-71313 e-mail: nakicenovic@iiasa.ac.at
DECPAC/Phase 1	International Atomic Energy Agency P.O. Box 100 Wagramerstrasse 5 A-1400 Vienna, Austria	I. Florin Vladu Tel. +43-1-2360-22773 Fax. +43-1-20607
EFOM	The European Commission DDG-XII F/1 200, rue de la Loi Brussels, Belgium	Pierre Valette Tel: +32-2-295-6356/3701 Fax: +32-2-296-302470621
ENPEP	International Atomic Energy Agency P.O. Box 100 Wagramerstrasse 5 A-1400 Vienna, Austria	H. H. Rogner Section Head Planning and Economic Studies Section H.H.Rogner@iaea.org
ESG	Swiss Federal Institute of Technology Center for Economic Research ORL Institute ETH Honggerberg CH-8093 Zurich, Switzerland	Peter Staub Tel: +41-1-632-4744 Fax: +41-1-632-1102
LEAP	Stockholm Environment Institute (Boston) Tellus Institute 11 Arlington Street Boston MA 02116-3411, USA	Charles Heaps Tel: +1-617-426-8090 Fax: +2-617-426-8303 E-mail: cheaps@tellus.com
MARKAL	IEA/ETSAP c/o ECN Policy Studies P.O. Box 1 1755 ZG Petten, Netherlands	Tom Kram Tel: +31-224-564431 Fax: +31-224-56338 e-mail: etsap@ecn.nl
MARKAL-MACRO	(See MARKAL)	(See MARKAL)
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MESSAGE-III	(See CO_2DB)	(See CO_2DB)
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ANNEX II

DESCRIPTIONS OF MAIN ELECTRICITY GENERATION TECHNOLOGIES

II.1. Coal fired power plants

II.1.1. Conventional pulverised coal combustion

Conventional pulverised coal combustion burns finely ground coal particles in a boiler with water-cooled walls. Steam is raised in these walls and in a series of heat exchangers. In the case of an electricity-only power plant, the steam is passed through a condensing steam turbine which drives the electricity generator. In the case of a cogenerating power plant, a back-pressure or extraction steam turbine is used. In a reheat steam cycle, the steam is brought back to the boiler, after being partially expanding through the steam turbine, and reheated to peak temperature again in order to improve overall power generation efficiency. This basic configuration is used in all steam-electric power plants.

The pressure at which steam is generated is a key design feature. In subcritical boilers, the steam pressure is kept below the ‘critical pressure’ of water, which is about 22 Mega-Pascals (MPa), or about 218 atmospheres. Supercritical boilers raise steam above this pressure. By doing so, the efficiency of power generation is improved, but the costs of the boiler, piping, steam turbine and control valves are increased. The materials of construction of these components must be resistant to the high-pressure steam and so are more expensive alloys. The choice of subcritical or supercritical design depends on the local balance of fuel costs, which are reduced by higher efficiency, and capital costs, which are increased due to more expensive materials.

The impurities contained in coal are released during combustion. In addition, nitrogen oxides (NO_x) are formed by the combustion process itself through chemical reactions with nitrogen contained in the coal and in the combustion air. Pollutants found in combustion gases include sulphur dioxide, nitrogen oxides, halogens, unburned hydrocarbons and metals. Ash remains from the non-combustible portion of the coal and from unburned carbon. Typically, half of the ash is collected in the bottom of the boiler and the remainder is carried along in the combustion gases as flyash. Various environmental control systems must be incorporated into the plant design to limit the formation of pollutants (sulphur and nitrogen oxides) or to remove them from flue gases.

The pollutants controlled from coal fired plants, and the levels to which they are controlled, are key cost factors. The tighter the emissions limits, the more expensive the pollution control systems will be to build and operate, and the more energy they will consume. A report published by the OECD International Energy Agency (IEA) summarises major pollution control standards for coal fired power plants in IEA Member countries [1]. The major pollutants of concern are airborne emissions of sulphur dioxide, nitrogen oxides and particulate matter.

Sulphur dioxide (SO_2) is controlled mainly by post-combustion flue gas desulphurisation (FGD) systems, usually based on ‘wet scrubbers’. The predominant wet scrubber design consists basically of a reaction vessel in which the SO_2 in the flue gas stream is absorbed by a wet slurry of limestone or other reagent. SO_2 removal efficiencies of 95% or more are possible. Other configurations are possible, including spray dryer systems, dry sorbent injection and regenerable systems [2]. The energy needed to operate a wet scrubber system consumes up to 1% of plant output and adds up to 100-250 US$/kW(e) to plant capital cost [3]. Energy consumption and costs are closely related to the required efficiency of SO_2 removal from the flue gases.

Nitrogen oxides (NO_x) are controlled by modifications to the coal combustion system itself, in order to minimise NO_x formation during combustion, and by post-combustion NO_x removal systems. Control of air within the combustion zone (overfire air) and the use of ‘low-NO_x’ burners are the two primary combustion system techniques used, which result in an immediate reduction in NO_x production of up to 60% compared to uncontrolled coal combustion. Low-NO_x burners are either the standard or the minimum NO_x control requirement in many countries. Capital costs for these burners are not a significant cost factor, typically adding only 10-30 US$/kW(e) to the total plant cost. If NO_x emissions must be reduced to levels below those obtainable using combustion modifications, post-combustion NO_x removal (de-NO_x) systems must be installed. Generally, selective catalytic reduction (SCR) systems are used for coal fired stations. These involve the injection of ammonia or urea into the flue gas and the catalytically enhanced reaction of the reagent with NO_x to form nitrogen and oxygen. SCR is the most effective de-NO_x technology, but is relatively expensive since the total volume of flue gas must pass through catalyst beds. The catalyst reactor adds some 50-90 US$/kW(e) to the plant cost and induces higher plant electrical consumption. The catalyst must be replaced periodically, adding to O&M costs.

Particulate matter consists mainly of very small ash particles that are carried along with the combustion gases. Control of particulate matter has been incorporated in nearly all coal fired power stations in industrialised countries for many years. Two basic systems are used for control of particulate matter emissions. *Electrostatic precipitators* function by drawing particulate matter to electrically charged plates placed along the flue gas path. *Fabric filters*, installed in 'baghouses', mechanically trap the airborne particles in a large number of fabric bags arranged in parallel, through which the flue gas flows. The choice of system depends upon particulate emission limits, flyash characteristics, total flue gas volume flow, and other factors.

Several advanced emission control systems are able to remove two or three of the major pollutant streams in a single system. For example, the 'E-beam' process irradiates the flue gas with high energy electron beams, and then uses chemical reagents to remove SO_2 and NO_x in a single process. Other catalytic and chemical combined removal processes are under development. However, these systems have not seen substantial commercial use yet.

Other systems normally are required to control pollution from solid or liquid discharges from coal fired stations. For example, wastewater from power plant processes and runoff from coal and ash storage areas typically is treated before release. In some cases, special ash treatment is required to stabilise leachable materials found in coal ash.

II.1.2. Fluidised bed coal combustion

Atmospheric fluidised bed (AFB) combustion of coal functions by burning coal in a 'bed' or dense cloud of coal particles that are aerodynamically suspended in a flowing air stream. The combustion chamber is held at atmospheric pressure (hence the name, 'atmospheric fluidised bed'). The airflow suspending the particles is sufficiently strong that a portion of the suspended coal and ash particles is carried out of the combustion chamber. The entrained particles are removed by dust collection cyclones and recirculated to the combustion chamber. Owing to this circulating behaviour of the particles, AFB is known also as 'circulating fluidised bed' combustion. As in conventional pulverised coal boilers, the heat released by combustion is captured in water-cooled walls to raise steam, and in a series of heat exchangers to cool the combustion gases. Heat exchangers cooling the recirculated coal and ash particles are used also for the production of steam in some designs. The steam raised may be subcritical or supercritical, although to date fluidised bed boilers have employed subcritical steam systems only. Power plants based on AFB combustion can be considered as a commercially proven technology.

Sulphur dioxide emissions can be controlled by the addition of limestone or other sorbent to the fluidised bed. The limestone captures SO_2 in solid form, primarily as calcium sulphate, and thus avoids the need for post-combustion flue gas desulphurisation. Although NO_x formation is minimised because of lower combustion temperatures, as compared to temperatures in conventional pulverised coal combustion, de-NO_x control still may be required. Fluidised bed plants can use the same de-NO_x systems as described above for conventional coal plants. Some form of particulate control typically is required also (e.g. electrostatic precipitator or baghouse).

Pressurised fluidised bed (PFB) plants are similar in design to AFB plants, with the exceptions that: the particles are suspended in a 'bubbling bed', with lower fluidising velocity than in AFB plants, and the particles are not circulated outside the combustion chamber; and, the combustion chamber is pressurised above atmospheric pressure. The higher pressure allows PFB plants to be combined with gas turbines, through which the hot combustion gases are expanded to drive the electricity generator and also to drive the compressor for pressurising the combustion air. Systems for cleaning the hot combustion gases must be used in this arrangement in order to protect gas turbine blades from entrained particulates and gas impurities. No commercial PFB plants have been constructed, although a number of demonstration plants have been built and operated.

II.1.3. Advanced steam cycles

The efficiency of steam power cycles, in both pulverised coal and fluidised bed boilers, can be increased by using steam above its supercritical pressure. Overall plant efficiency can be increased from roughly 38% (based on lower heating value) using subcritical steam cycles to 42-45% with supercritical steam. Steam conditions above 25 MPa (245 atmospheres) and 566 °C, or 'ultra-supercritical' conditions, have the potential to increase cycle efficiencies an additional 2-3 percentage points. Special steels capable of resisting higher temperatures and pressures while still resisting corrosion are key to the use of supercritical cycles. Other cycle improvements, such as double reheat, once-through steam heating, enhanced feedwater heating, and reduced piping pressure drops also can improve cycle efficiency, at the cost of increased expense for equipment and materials.

Pollution control systems for coal fired plants are the same regardless of the steam pressure employed. For example, FGD, low-NO_x burners and flue gas de-NO_x, and particulate control typically would be required whether the plant employed a subcritical or supercritical steam cycle. Plants employing more efficient steam cycles have marginally less expensive pollution control systems because less coal is burned, and consequently less pollutant is produced, per unit of electrical output.

II.1.4. Integrated gasification combined cycle

Integrated gasification combined cycle (IGCC) plants convert coal to a gaseous fuel, and then burn this fuel in a combined cycle gas turbine (CCGT - see description below). The principal components in IGCC plants are: a coal gasification facility, typically including an oxygen production plant and gas cleaning facility; and, a CCGT power plant. The gasifier functions by only partially combusting the coal. This partial combustion provides enough energy to drive off volatile compounds and to cause gasification reactions that create hydrogen, carbon monoxide and methane gas. This 'synthetic natural gas' (syngas) also contains sulphur compounds which are removed in gas cleaning systems. Compared to conventional coal combustion, the sulphur compounds are present at relatively high concentration and therefore can be removed at high efficiency (98% or greater) and at moderate cost.

A key design feature of the gasification plant is the choice of air or pure oxygen as the source of oxygen for the syngas production step. Most plants to date have used oxygen. This choice means that key process components, particularly the gasifier, heat exchangers and gas cleaning systems, are smaller because they do not need to process the large volume of nitrogen (80%) that is present in air. Also, the heating value of the syngas produced with oxygen is closer to that of natural gas, than is the syngas produced with air. The gas turbine therefore requires less modification to burn the syngas produced in an oxygen consuming gasifier. The main disadvantage with using oxygen is that a dedicated cryogenic oxygen production facility must be used. There has been considerable development work on gasification systems using air, but few past or presently operating IGCC systems have used them. Various gasifier types have been developed, including entrained flow, fluidised bed and fixed bed. Entrained flow gasifiers, typically using oxygen, have dominated IGCC applications to date.

The clean syngas from the gasification facility is burned in a CCGT plant of basically standard configuration. There are various opportunities for integration of the combined cycle and gasification facility through exchange of steam flows and air flows, which tends to increase thermal efficiency at the expense of greater process and operational complexity. Advances in gas turbine technology will tend to improve the efficiency and cost effectiveness of IGCC plants.

II.2. Gas fired power plants

Gas fired power plants can be, and conventionally have been, based on steam cycles as described above for coal fired power plants. However, the gas turbine is the most popular technology today for generating electricity from natural gas. Therefore, the technology description given below is for this type of gas fired power plant.

II.2.1. Basic features of gas turbine power plants

Gas turbines, also known as combustion turbines, have been in existence since World War II, when they were developed for use as aircraft engines. In the application to power production, the gas turbine is used to drive an electricity generator. In an ‘open cycle’ gas turbine plant, the gas turbine exhausts to the atmosphere. However, the exhaust stream is sufficiently hot that it can be used to raise steam for producing additional electricity using a steam turbine, thereby improving the overall efficiency of power production. The combination of gas and steam turbines is called a ‘combined cycle’ gas turbine (CCGT). Gas turbine technology for power production has benefited greatly from technical developments in jet aircraft engines. Currently, CCGT plants have thermal efficiencies of 50 to 55%. The use of both open cycle and combined cycle gas turbines for power production has benefited also from the increased availability of gas supplies and the liberalisation of gas markets in many countries.

In CCGT plants, heat recovery steam generators typically produce steam at two pressure levels, in order to maximise the heat recovery from the gas turbine exhaust stream. Boilers on advanced turbines will take advantage of higher exhaust stream temperatures by using three pressure levels of steam.

Gas turbines are compact devices that are produced in factory series. Also, the steam turbines and the boilers used to recover heat from the turbine exhaust (heat recovery steam generators) are relatively standardised. The use of standardised components allows manufacturers to market modular power plants with reduced design and construction costs.

II.2.2. Pollution control systems for gas turbine power plants

Natural gas normally contains little or no sulphur. Therefore, natural gas fired power plants usually do not require flue gas desulphurisation systems. However, as with coal fired plants, nitrogen oxides are produced during the combustion process. Low-NO_x burners can reduce the production of NO_x in gas turbine combustors and now are almost standard on new turbines. Injection of steam or water into the combustors can be used also to reduce NO_x production, but this reduces thermal efficiency and therefore is less common in new units. In areas where strict NO_x emission regulations are in effect, de NO_x removal systems, mainly selective catalytic reduction, may be needed.

II.2.3. Advanced gas turbine power plants

Advanced gas turbines currently under development will have efficiencies approaching 60%, achieved through the use of high combustion temperatures, steam-cooled turbine blades, and more complex steam cycles. A number of advanced power cycles involving gas turbines are under development or being demonstrated. These aim to maximise the efficiency of the steam cycle or to integrate more tightly the gas and steam cycles. Examples are: HAT and CHAT cycles (humid air turbine and cascaded humid air turbine); intercooled, reheat turbine cycles; STIG cycle (steam injected); Kalina cycle (ammonia/water steam cycle); and thermo-chemical exhaust heat recovery [4].

II.3. Fuel cells

Fuel cells convert hydrogen, light hydrocarbons or carbon monoxide directly into electricity via a thermo-chemical reaction carried out in a ‘cell’ with no moving parts. For most fuel cells, natural gas must be converted, in a reformer, into a hydrogen-rich fuel before feeding it to the conversion cell. In the cell, the hydrogen reacts with oxygen from the air to produce direct current (DC) electricity, with water vapour as an exhaust by-product. In some fuel cell designs, the exhaust gas may be sufficiently hot to drive a steam cycle or other heat recovery system. A power conditioner is required to convert the electricity from DC to alternating current (AC) for supply to conventional electricity transmission and distribution systems. The relatively low temperature thermo-chemical reaction of fuel produces very little NO_x, as compared to normal combustion, so de-NO_x systems are not required.

Fuel cells have several different basic designs, all having an anode and a cathode, with an electrolyte between the two. Molten carbonate and phosphoric acid (alkaline) fuel cells rely upon liquid electrolytes, while solid oxide fuel cells use zirconium oxide as a high-temperature solid electrolyte. Operating temperatures vary among the different fuel cell types, from 80 °C in alkaline fuel cells to 1000 °C in solid oxide fuel cells. The cells most suitable for large baseload power generation appear to be molten carbonate fuel cells and solid oxide fuel cells [5].

At present, fuel cell systems are not cost competitive with fossil fuel fired or nuclear power plants. High capital cost remains the most important disadvantage of current fuel cell designs.

II.4. Nuclear power plants

The principal types of nuclear power plants available on the market today are based on light water reactors (LWRs) or pressurised heavy water reactors (PHWRs). Light water reactors include pressurised water reactors (PWRs) and boiling water reactors (BWRs). At present, LWRs represent more than 85 per cent of the nuclear capacity in operation worldwide (around 64 per cent are PWRs and 22 per cent are BWRs) and nearly 80 per cent of the capacity under construction. PHWRs represent some 5 per cent of the installed capacity in the world and nearly 15 per cent of the capacity under construction.

II.4.1. Basic features of conventional nuclear power plants

Each reactor type is characterised by the choice of a neutron moderator and a cooling medium, which lead to some differences in fuel designs. LWRs use light water (ordinary water, H_2O) as moderator and coolant. In PWRs, the water is prevented from boiling by keeping the coolant at a high pressure, while in BWRs the water is allowed to boil in the reactor core. In either type, the heat generated by nuclear fission in the reactor core is used to raise steam, either inside or outside the core, which drives a steam turbine-generator to produce electricity.

Both LWR types require enriched uranium fuel (containing more U^{235}, the fissile isotope, than natural uranium) in order to maintain a chain reaction in spite of the absorption of neutrons by the moderator. Fuels used in LWRs of current generation use uranium enriched to some 3-4% in U^{235}, while natural uranium contains 0.7% U^{235}. LWRs also can use fuel containing recycled materials, plutonium and uranium, recovered through reprocessing of spent fuel. PHWRs use heavy water (deuterium oxide, D_2O) as coolant and moderator. This choice makes it possible to utilise natural uranium as fuel, owing to the fact that D_2O absorbs fewer neutrons than H_2O. The core arrangement of PHWRs is more complex than that of LWRs, due to the use of separate flow channels for coolant and moderator. However, this complexity does allow PHWRs to be refuelled while operating, whereas LWRs have to be shut down for refuelling.

For LWRs, the main front-end (i.e. before fuel loading in the reactor) fuel cycle steps are: uranium mining and milling; conversion; enrichment; and fuel fabrication. For PHWRs, the enrichment step is not necessary. As enrichment accounts for some 40 per cent of the levelised front-end fuel cost [6], fuel cycle costs are lower for PHWRs than for LWRs. However, this saving is offset at least partly by the cost of producing D_2O (an enrichment step in itself). At the back-end of the fuel cycle (i.e. after unloading of spent fuel from the reactor), two options are available: once-through, or direct disposal of spent fuel; and reprocessing/recycle. In the first option, spent fuel is conditioned, after interim storage for cooling, into a form suitable for final disposal in a high level radioactive waste repository. In the second option, spent fuel is reprocessed to separate materials (plutonium and uranium) that can recycled for use in reactor fuel, and the residual wastes (fission products) are conditioned, after interim storage for cooling, for disposal in a high level waste repository. There appears to be little difference in overall cost between the once-through and recycling options [6]. PHWRs usually operate on the once-through fuel cycle, while LWRs operate on either the once-through or recycle fuel cycle. For all reactor types and all fuel cycle options, radioactive waste arisings at each step of the fuel cycle are sorted, according to their level of radioactivity, and conditioned for disposal in low level, intermediate level or high level waste repositories.

II.4.2. Advanced nuclear power plant designs

Advanced nuclear power plant designs and concepts are focusing on shorter construction times, lower costs, improved reliability and enhanced safety [7]. Design improvements have been introduced mainly in an evolutionary fashion through modifications that take advantage of successful, proven design features and new technological developments, including in non-nuclear areas such as control and instrumentation.

Several nuclear power plants commissioned recently already incorporate a number of advanced reactor key features. Examples are: the first two 1315 MW(e) advanced boiling water reactor (ABWR) units, Kashiwasaki Karima 6 and 7, commissioned in 1996 and 1997 in Japan; and, the N4 1400 MW(e) advanced pressurised water (APWR) units, Chooz B1 and B2 and Civaux 1, in France.

Advanced light water reactors (ALWR) under development include large size units [1200 to 1300 MW(e)], and mid-size plants [around 600 MW(e)] using passive safety systems and inherent safety features. Important programmes in ALWR development were initiated in the mid 1980's in the United States, including large and mid-size APWRs and ABWRs. Two large evolutionary plants, the 'System 80+' APWR and the ABWR received design certification from the US Nuclear Regulatory Commission (NRC) in 1997. The AP 600 mid-size APWR is under NRC review aiming towards final design approval in 1998. In Europe, France and Germany are developing jointly a 1500 MW(e) advanced PWR, the European pressurised water reactor (EPR), with enhanced safety features meeting the requirements of the safety authorities in those two countries. ALWR development efforts are pursued also in other countries, such as China, Finland, Japan, Republic of Korea and Russia. Advanced evolutionary heavy water reactors (APHWRs) are under development in Canada and India.

All advanced reactors under development are aiming towards enhancing the economic competitiveness of nuclear power as compared to fossil fuelled power plants, especially gas fired plants, while maintaining and improving the already high safety levels. Owing to the high capital cost of nuclear power plants, designers have focused their efforts on design simplifications aiming towards reducing capital costs. Significant capital cost reduction can be obtained by design standardisation, building multiple units on the same site, placing series orders, shortening construction times and improving project management [8]. The benefits of standardisation and series orders are illustrated, for example, by the experience obtained in the REP-2000 series in France, which is estimated to have led to savings of some 20% in capital costs [9]. Standardisation and series orders also have induced economic benefits through, for example, reducing the unit costs (i.e. per kWh of electricity produced) of staff training and spare parts.

Shortening construction times reduces interest during construction, which is a significant component of nuclear investment costs. Progress has been made already in this regard; for example, nuclear units commissioned recently in Japan and the Republic of Korea were built in 4 to 5 years, which is a significant improvement over experience in some other countries. At the same time, advanced reactors are designed to have longer operating lifetimes (50 to 60 years) than current plants (30 to 40 years), which lead to decreases in levelised electricity generation costs.

Simplification is a key goal in the design of advanced reactors, since reducing the complexity of the nuclear steam supply system (the 'nuclear island') produces benefits through: lower costs; easier and cheaper operation and maintenance; higher reliability; and improved safety. Advanced reactor designs aim toward: more compact and simplified plant layout; smaller buildings and structures; fewer safety related valves, pumps and piping; and simplified steam turbines.

Another area of cost reduction is in fuel utilisation. Advanced reactor designs aim to improve fuel energy utilisation ('fuel burn-up') and lower the total cost of fuel fabrication and other cost components related to the quantity of fuel handled.

II.5. Other power plant technologies

II.5.1. Oil and biomass fired power plants

Steam power plants can be fuelled with oil and biomass, as well as with coal or natural gas. The basic technologies are the same as for coal fired boilers, as described above. However, the technical features of the boilers and auxiliary systems vary according to the fuel. For example, the different combustion characteristics influence the radiant heat transfer within the combustion chamber. Also, flue gas heat exchanger designs vary markedly according to the different composition and ash loading of the flue gases. FGD and de-NO_x systems may be required, depending on the sulphur content and combustion characteristics of the fuel. In the case of oil, the requirements for soot-blowing and ash removal are much less, compared to coal fired boilers, owing to oil's low ash content. FGD and de-NO_x typically would be required for new baseload oil-fired plants.

Biomass is relatively non-uniform and has a higher moisture content than fossil fuels. These characteristics make fluidised bed combustion an effective technology for biomass combustion. Biomass may be consumed also in IGCC power plants similar in basic process design to coal fired IGCC plants. The gasifier choice depends strongly on the biomass characteristics, but, as in simple biomass combustion, fluidised bed gasifiers are well adapted for biomass. The economic optimum size for biomass fuelled plants is smaller than for fossil fuelled plants because of the limited quantity of biomass that typically is available within a given distance from the power plant. Beyond certain, fairly short distances, the cost of transporting biomass, with its high moisture content and low heat value, to the plant becomes excessive.

II.5.2. Wind turbines

Wind energy is one of the fastest growing renewable energy sources for electricity generation, in particular in countries of the OECD. During the period from 1990 to 1995, electricity production by wind power increased by an average of more than 70% per year in OECD countries, with particularly rapid growth in Germany, the United Kingdom and Spain. This growth has been made possible by decreasing costs for wind power, combined with government policies designed to promote its implementation.

The technology of wind turbines has shown rapid progress in recent years. The predominant design is the horizontal axis turbine in which two or three airfoils, power transfer gearing and electricity generator are mounted at the top of a tower. Unit capacities of series-produced machines have increased steadily as experience has been gained with their design and operation. For example, Zond Corporation (USA) reports that wind turbine sizes increased from 25 kW(e) in 1981 to 750 kW(e) in 1997, a factor of 45, while the turbine capital cost increased by only a factor of nine. Average size of wind turbines installed in Denmark increased from around 30 kW(e) in 1983 to 350 kW(e) in 1995. The trend to increasing size reduces unit investment cost, through economies of scale in wind turbine design, construction and operation.

Another key factor in wind turbine cost is the weight of equipment mounted on the tower. The newer systems are lighter, thereby reducing the design loads on the towers and leading to lower cost towers. The new systems also tend to be simpler and more reliable because of fewer parts. The combination of design factors and improved operational experience has lowered unit capital costs by 50% and generation costs by two thirds, compared to respective values in the early 1980s.

REFERENCES TO ANNEX II

[1] INTERNATIONAL ENERGY AGENCY, Coal Information 1996, OECD, Paris (1997).

[2] SOUD, H.N. AND TAKESHITA, M., FGD Handbook - 2nd Edition, IEACR/65, IEA Coal Research, London (1994).

[3] TAKESHITA, M., Air Pollution Control Costs for Coal-Fired Power Stations, IEAPER/17, IEA Coal Research, London (1995).

[4] KEHLHOFER, R., Combined-Cycle Gas and Steam Turbine Power Plants, Fairmont Press, Lilburn, GA, USA (1991).

[5] HIRSCHENHOFER, J.H. AND MCCLELLAND, R.H., "The Coming of Age of Fuel Cells", Mechanical Engineering, October 1995, pp. 84-88, American Society of Mechanical Engineers, New York (October 1995).

[6] NUCLEAR ENERGY AGENCY, The Economics of the Nuclear Fuel Cycle, OECD, Paris (1994).

[7] JUHN, P.-E., KUPITZ, J. AND CLEVELAND, J., "Advanced Nuclear Power Plants: Highlights of Global Development", Bulletin of the IAEA, Vol. 39, No. 2, Vienna (1997)

[8] NUCLEAR ENERGY AGENCY, Means To Reduce the Capital Costs of Nuclear Power Stations - A Report by an Expert Group, OECD, Paris (1990).

[9] BACHER, P., "REP-2000, The Next Generation of EDF's Nuclear Reactors", Power Technology International, Autumn 1995, pp. 79-82 (1995).

ANNEX III

ENVIRONMENTAL IMPACTS OF ELECTRICITY PRODUCTION

III.1. Introduction

Environmental impacts related to the operation of Electrical Energy Systems (EES) comprise the direct or indirect adverse effects and disadvantageous phenomena that must be taken into consideration when discussing the EES. Impacts are connected with the production, transmission, distribution and utilisation of the electrical energy, in both normal operation and accident situations. In this sense, the environmental impacts related to EES result from numerous complex phenomena and interactions, starting with the health effects and injuries connected with the exploration and mining of the fuels, through the emissions of different polluting materials, land disturbances, etc., up to the utilisation of the electricity for producing energy services.

Because of the complexity, generally it is not possible to deal with all of the potential burdens, pathways and types of impacts in a single environmental impact study (EIS). The approach usually taken is to focus the EIS on identifying and analysing those which appear, on a first review, to have the largest potential impacts in the specific situation. Owing to this approach, however, it is possible that some eventually important impacts will be overlooked. Also, this approach means that the potential environmental impacts of the different candidate energy sources and generation technologies are not fully evaluated. Therefore, the resulting comparative assessment will not incorporate all externalities for the different options, which could lead to a ‘less than best’ expansion strategy being selected. Thus, it is necessary to review and monitor the performance of the strategy in order to determine whether any unforeseen damages are occurring, and to mitigate such effects.

The level of awareness of health and environmental impacts of energy systems, as well as the technical and economic capability to mitigate impacts, is not the same in all countries and regions of the world. In some countries, protection of human health and the environment is given high priority, and sophisticated technical, regulatory and management systems have been implemented to mitigate impacts. In other countries, in particular those with a shortage of money for capital investment, protection of health and the environment, although recognised as being needed, may be given a lower priority than, for example, overcoming a shortage of electricity supply. One of the main objectives of the integrated approach to electricity system analysis, as described in this reference book, is to promote the use of comparative analysis studies aiming towards identifying strategies for achieving both adequate electricity supply and protection of human health and the environment. In order to assist in efforts to meet this objective, this annex attempts to highlight the overall impacts connected with the EES, and to provide a kind of tabular ‘check list’ of the types and approximate magnitudes of impacts associated with different energy sources and chains for electricity generation.

However, it has to be emphasised that the description and tables presented in this annex are not exhaustive, and the material should be used only as a starting point in the assessment of health and environmental impacts of energy systems.

The material presented in this annex is based on information drawn from published reports [1, 2, 3, 4, 5, 6], supplemented in some cases by unpublished material provided by the contributing experts.

III.2. Brief description of environmental impacts connected with the EES

When discussing and assessing the environmental impacts connected with the EES, it is necessary to compile, to the extent possible, a list of all possible impacts and to make an initial estimate of their relative importance. Also, owing to the fact, as discussed above, that it is not possible to take into consideration all the impacts in detail, it is necessary to estimate the range of values for any impacts that are known to have been omitted from the EIS.

Many different classifications of health and environmental impacts can be found in the published literature. Each classification may be useful for certain purposes and each can help in developing a better understanding of the topic. One suitable classification, that frequently is used, distinguishes the impacts that are related to *human activities* from those that are a result of *natural processes or phenomena.* Those impacts which result from human activities are called *anthropogenic impacts*. The anthropogenic impacts related to EES can be divided for convenience into *fuel-related impacts* and *non-fuel-related impacts*. The fuel-related impacts refer to those that result from the burning of fossil fuels, and sometimes are called *pyrogenic impacts*.

Depending on whether the impact results from a direct effect or is due to an alteration in the human or natural environment, that subsequently leads to an impact, the impacts can be sub-divided into, respectively, primary and secondary impacts. Some examples of the impacts falling into each of these categories are the following:

1) **primary impacts:**
    - *ecological impacts*: atmospheric, vegetal, terrestrial, lithospheric or biospheric impacts, including land disturbances in the area occupied by different elements of the EES (e.g. power plants, electrical substations, overhead power lines, waste storage and disposal);
    - *fatal and non-fatal accidents*: including those affecting the workers and employees and those affecting the general population;
    - *chemical (organic, inorganic) impacts*: including those to air, land and water environments;
    - *physical impacts*: including radiation effects, noise, modification in visibility, heat rejection to air and water, electro-magnetic field effects, etc.;
    - *hydrological impacts*: including changes in natural stream flows, effects on water use, water pollution, sedimentation, changes in precipitation patterns, etc.;
    - *mechanical impacts*: depletion of forest cover, soil erosion, dust emissions, spillage to land and water, etc.
2) **secondary impacts:**
    - reactions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x), with formation and deposition of dry and wet acid compounds, leading to acidification of water and land and causing erosive damages to buildings and monuments;
    - reactions of hydrocarbons into photochemical smog and ozone, leading to health effects and impairment of visibility;
    - beneficial effects of: replacing fuel burning by electricity at point of energy end-use; replacing fuel by primary electricity (i.e. hydro or nuclear); replacing fossil generation by renewable energy; etc.

The environmental impacts can be listed also according to the types of effects and the pollutants that contribute to those effects, for example:

- *greenhouse effects (direct and indirect)*: CO_2, CH_4, NO_x, N_2O, CFCs, CO, NMVOC (non-methane volatile organic compounds);
- *ozone depletion*: CFCs (halogenated hydrocarbons)
- *acidification*: SO_2, NO_x
- *photosmog*: VOC (volatile organic compounds), NO_2
- *nitrification*: NO, phosphate (PO_4)
- *radiation doses*: tritium, radon, C-14, Kr-85, Sr-90
- *human toxicity*: dioxins, heavy metals (As, Cr, Hg, Pb)
- *exotoxicity*: Cr, Cd

- *bioaccumulation*: POPs (persistent organic pollutants), DDT
- *biological degradation*: pollution induced diseases, mutations, reduced fertility
- *vegetal degradation*: pollution induced yield losses
- *odours*: NH_3, butyric acid, H_2S
- *noise, vibration*: heavy rotating elements, engines and motors
- *surface alternation*: land disturbances by power plants, overhead lines, pipelines
- *visual disturbances*: large facilities, smoke, water vapour, overhead lines
- *micro-climate changes*: water vapour from thermal plant cooling towers, evaporation from large hydro reservoirs
- *material damages*: acid rain induced corrosion and damage to buildings and monuments
- *resource depletion*: material and fuel requirements for energy systems

When discussing the environmental impacts connected with electricity generation, the emphasis generally is on pollutant emissions to the atmosphere. This focus is owing to the fact that atmospheric emissions from fossil fuel fired thermal power plants are an important contributor to the overall emission balance in many countries. The focus is due also, at least in part, to the existence of good methods and tools for measuring atmospheric emissions and for assessing their impacts, while the measurement and assessment methods are not as well developed for some other pollutants (e.g. those to land and water). It should be kept in mind also that pollutant emissions from fossil fuelled power plants are connected with their normal operations. For nuclear power plants, on the other hand, the emissions are very low during normal operation, and the main concern is related to potential accident situations, which usually are assessed through the use of probabilistic risk assessment (PRA) tools (see Annex V).

In order to select the most suitable control technology for limiting or reducing the pollutants emitted into the atmosphere, it is necessary to know the mechanism and in which part of the energy system (e.g. mining, processing, power plant, waste handling) the pollutants are produced. For example, the organic or inorganic atmospheric pollutants originate from a number of sources, including:

- components naturally present in the fossil fuel (e.g. ash, soot, heavy metals);
- interaction between components of the fuel and the combustion air (e.g. SO_2, NO_x, CO_2, CO);
- interactions between different pollutants or between pollutants and the atmosphere (e.g. photochemical reactions, acidification).

The emission limits for different pollutants are based on standards established in each country, and the limits depend on the characteristics of the area in which the source of the pollution is located. If the uncontrolled emission from a facility, or from all facilities within a region, would exceed the established limit, regulations require that the emissions have to be mitigated through a variety of possible measures, such as:

- reducing the quantity of fuel burned (e.g. increasing the efficiency of the power plant, switching to a fuel with higher heat content);
- increasing the quality of the fossil fuels (e.g. washing to reduce ash and sulphur content, beneficiation to increase heat content);

- switching to a different fuel having lower natural pollutant content (e.g. switching from coal to oil or natural gas, switching from heavy fuel oil to light oil or natural gas, switching from high sulphur to low sulphur coal);
- modifying the combustion characteristics (e.g. installation of low NO_x burners, multi-staged firing, repowering pulverised coal combustion to fluidised-bed combustion);
- installing post-combustion flue-gas cleanup systems (e.g. FGD, de-NO_x, dust removal).

III.3. Potential environmental impacts of different energy systems

In the following sections of this annex, an attempt has been made to provide a detailed description and tabular compilation of the potential environmental impacts from different energy sources and chains for electricity generation. The purpose is provide an indicative, but not exhaustive, 'check list' of the impacts that should be taken into consideration in a comprehensive environmental impact assessment (EIA).

The material presented in the following sections and tables was derived mainly from work carried out by the Working Group on Environmental Costs of the Brazilian Co-ordinating Committee of Environmental Activities of the Power Sector (COMASE) [1]. This working group has: made a detailed analysis of the different fuels and technologies that could be considered as candidates for the expansion of the Brazilian electricity system; tried to identify and quantify the impacts and include them in comparisons of the different expansion options; attempted to internalise some of the social and environmental costs ('externalities'), when possible. The fuels considered for use in Brazil were: coal, oil, gas, biomass, nuclear and hydro. Owing to the importance of hydro-power in the Brazilian electricity supply system, this technology was treated extensively in the COMASE analysis. Also, large hydro-power projects usually require implementation of large capacity, long distance electricity transmission lines together with transformer and switching stations. Therefore, the potential impacts related to these facilities were considered also. The analysis carried out for conventional thermal and nuclear power plants was expanded to cover international experience as well as the experience in Brazil.

The original work of the COMASE Working Group considered only the impacts that are directly connected with the power sector. However, in the material presented in this annex, that original work has been complemented by adding consideration of impacts from activities that, although not strictly within the boundaries of the power sector, are indirectly connected with power production (e.g. fuel resource exploration and extraction, fuel processing and transportation).

For the purpose of this annex, social and/or environmental impacts (externalities) are understood to comprise 'any alteration of the physical, chemical and biological characteristics of the environment - caused by any form of material or energy resulting from human activities - which directly or indirectly affects human health, safety and population welfare, social and economic activities, the biota, sanitary and aesthetical conditions of the environment, and the quality of the environmental resources, and which are not included already in the price of electricity'.

Attention must be called to the fact that, in preparing the tabulations of impacts (Tables III.1 to III.14), an attempt was made to prepare a reasonably comprehensive list of known potential impacts and relevant mitigation measures, with the aim of covering situations that might be encountered with projects in any region. It should not be construed that all of the listed impacts will occur in every plant. On the other hand, a particular project or location may encounter impacts that are not included in the tables. Therefore, it is emphasised again that the tables are an indicative, but not exhaustive, 'check list' of issues that need to be examined in order to assess their potential to cause serious impacts. It should be noted also that Tables III.1 to III.10 are limited to impacts that are associated directly with the power plant. Impacts connected with other components of the energy chains are discussed in Section III.4 (Full Energy Chain Impacts) and presented in Tables III.11 to III.14.

III.3.1. Hydro-electric power plants

Emissions from hydroelectric systems include:

- emissions related to dam construction;
- emissions from decomposition of submerged biomass in hydroelectric reservoirs;
- emissions from fossil fuel fired, peak load plants. This component is included in the inventory of emissions from hydro power plants, because it is a common practice, in predominately hydro-electric systems, to meet the peak load with thermal plants.

When creating hydroelectric reservoirs, land surfaces containing phytomass (i.e. trees, grass, etc.) are flooded. The submerged phytomass undergoes anaerobic decomposition into greenhouse gases (GHGs) such as CO_2 and CH_4 (methane), with the rate of decomposition depending on the types of phytomass and the physical and chemical properties of the water. The main conditions influencing decay rate and types of emissions are:

- water temperature;
- water quality, acidity, dissolved oxygen, oxidation potential;
- light intensity;
- pressure and reservoir morphometry.

Tables III.1 to III.3 aim towards identifying the social and environmental impacts due to planning, construction and operation of hydro power plants. The tables are structured as follows:

Column 1: Identifies the relevant environmental factors. Environmental factors can be defined as those factors that comprise the environment or eco-system. An environmental factor is an element or component that performs a specific function or has a direct influence on the operation of the environmental system or eco-system. The following are pertinent examples:

- physical environment : water resources, climate, seismicity, soil, water quality, etc.;
- biotic environment: vegetation, aquatic fauna, terrestrial and winged fauna, etc.;
- social, economic and cultural environment: economic activities, health, education, sanitation, population aspects, archaeological assets, etc.

Column 2: Shows the social and environmental impacts that might occur to each environmental factor.

Column 3: Indicates the time stage at which the impact might occur (i.e. during project planning, construction or operation).

Column 4: Identifies programmes and measures that could be used to mitigate the impacts or to compensate the population, directly or indirectly affected by the project, for the damages caused.

III.3.2. Transmission lines and transformer/switching stations

Tables III.4 and III.5 cover the social and environmental impacts related to electricity transmission lines, and Tables III.6 and III.7 present information for transformer/switching stations. Consideration was given to only those transmission lines having voltage levels of 69 kilovolts (kV) or higher. The tables are structured as follows:

Column 1: Identifies the possible causes of social and environmental impacts. The potential severity of the impacts was not a factor in the selection of the listed impacts, since the severity will vary depending on the specific conditions of each project.

Column 2: Shows the types of social and environmental impacts that might occur due to those causes.

Column 3: Indicates the time of occurrence (i.e. during the planning phase, construction or operation).

Column 4: Indicates the location of the potential impact (i.e. whether in urban or rural areas).

Column 5: Identifies programmes and measures that could be used to mitigate the impacts or to compensate the population, directly or indirectly affected by the project, for the damages caused.

III.3.3 Thermal power plants

Table III.8 summarises the potential social and environmental impacts related to the planning, construction and operation of conventional thermal power plants (coal, diesel oil, fuel oil, natural gas and biomass). As for other facilities, the impacts that actually occur will depend on the region where the plant is situated, the plant technology and fuel type, and the type and pollutant removal efficiency of any control systems installed.

Also, the level of experience is rather limited for some types of thermal power plants. For example, the experience with biomass fuelled plants is quite limited in comparison with plants burning pulverised coal. Therefore, the impacts described here for biomass plants should be considered as being only indicative. Table III.8 has the following structure:

Column 1: Identifies the possible causes of social and environmental impacts. The potential severity of the impacts was not a factor in the selection of the listed impacts, since the severity will vary depending on the specific conditions of each project.

Column 2: Shows the types of social and environmental impacts that might occur due to those causes.

Column 3: Indicates for which types of fuels the impacts are likely to occur. In general, the same types of impacts are likely to occur for all fuel types, with the magnitude of the impacts being the only significant difference.

Column 4: Indicates the time of occurrence (i.e. during the planning phase, construction or operation).

Column 5: Identifies programmes and measures that could be used to mitigate the impacts or to compensate the population, directly or indirectly affected by the project, for the damages caused.

III.3.4. Nuclear power plants

Table III.9 presents the social and environmental impacts due to the planning, construction and normal operation of nuclear power plants. The table is intended to be quite general, since the precise impacts of a particular plant depend on the type of nuclear power plant and fuel cycle technologies used, management practices and site conditions. The impacts from nuclear energy are somewhat different in character from those of conventional power plants, in particular because the potential impacts from low probability/high consequence accidents (see Annex V) have to be considered, in addition to the impacts resulting from normal operation. The potential impacts in accident situations are presented in Table III.10. Such accidents also need to be considered for hydro power and fossil fuelled energy systems, but in actual practice they usually are ignored. Tables III.9 and III.10 have the following structure:

Column 1: Identifies the possible causes of social and environmental impacts. The potential severity of the impacts was not a factor in the selection of the listed impacts, since the severity will vary depending on the specific conditions of each project.

Column 2: Shows the types of social and environmental impacts that might occur due to those causes. Most of the impacts indicated in the table occur only when the normal operation limits are exceeded, and in this situation, the level of potential consequences will vary, depending on the plant location and the type and characteristics of the process that initiated the abnormal event. Mitigation actions are important factors also in mitigating the potential impacts. The potential impacts are listed in a generic form, without considering such specific characteristics or the effectiveness of measures aiming at avoiding and/or mitigating those impacts.

Column 3: Indicates the time of occurrence (i.e. during the planning phase, construction or operation).

Column 4: Identifies programmes and measures that could be used to mitigate the impacts or to compensate the population, directly or indirectly affected by the project, for the damages caused. Such measures can be adapted suitably to different types of nuclear plants, either during the initial design of the plant or as retrofits to an existing plant. Many of the measures indicated can be implemented simultaneously.

TABLE III.1. HYDRO-ELECTRIC POWER PLANTS: IMPACTS ON THE PHYSICAL ENVIRONMENT

Environmental factor	Impacts	TO*	Measures/Actions/Projects/Programmes
Water resources	Modification of the hydrology regime, reducing high or low water levels and increasing water residence time in reservoir	C/O	Hydro-sedimentary monitoring of river basin Adaptation of the operational rules of the power plant Monitoring of the use of soil
	Modification of water flow downstream during filling of the reservoir and/or river diversion	C/O	Mechanisms to guarantee minimum water flow
	Reservoir silting and erosion of slopes upstream and downstream (slope stability)	C/O	Hydro-sedimentary monitoring Monitoring of soil use and vegetation cover Slope control, plantation of bordering wood, talus control, etc. Co-ordination with municipalities, states, land owners and/or tenant farmers and environmental organisations regarding soil use in the reservoir basin
	Interference with multiple uses of hydro resources: navigation, irrigation, water supply, flood control, leisure, tourism etc.	C/O	Make compatible river basin use Enhancement of plant operating rules Mechanism that guarantee a minimum water discharge
	Rise of ground water table	C/O	Monitoring of ground water table
Climate	Interference with local climate	C/O	Climate monitoring
Seismicity	Induction of earthquakes	C/O	Seismic monitoring
Soil and mineral resources	Interference with mineral activities Loss of mineral potential	C	Fast exploitation of existing deposits and potential resources in the reservoir area Identification of alternative deposits Compensation for mineral deposits Development of advanced techniques for underwater exploitation
	Erosion of river banks	C/O	Monitoring of erosion, transport and deposition of sediments Settlement of river banks (planting of bordering trees, talus control, etc.)
	Degradation of areas used for exploitation of construction material and by the temporary civil works	C/O	Reintegration of site works and recovery of degraded areas
	Interference with soil use	C	Intensification of agricultural exploitation and timber removal in the reservoir area Zoning, monitoring and control of soil use Co-ordination with municipalities, states, land owners and/or tenant farmers and environmental organisations regarding soil use in the reservoir basin

*Note: TO: time of occurrence. P: planning, C: construction, O: operation

(Table III.1 continued next page)

TABLE III.1. HYDRO-ELECTRIC POWER PLANTS: IMPACTS ON THE PHYSICAL ENVIRONMENT (CONT.)

Environmental factor	Impacts	TO*	Measures/Actions/Projects/Programmes
Water quality	Modification of water environment from lotic (river) to lentic (lake) Modification of the physical-chemical and biological infrastructure of the environment Deterioration of water quality (endangering water supply and plant equipment, etc.) Creation of conditions favourable for development and diffusion of etiologic vectors and agents of diseases Contribution of sediments, agrotoxic chemicals and fertilisers due to the occupation of river basin	C/O	Monitoring of water quality Mathematical modelling to support decision making process Cleaning reservoir area Control of proliferation of algae, aquatic vegetation and other organisms Alternative water supply for affected population Consistency of plant material and equipment with expected water quality in reservoir Implementation of means to control water quality (operating rules, aeration systems, high water intake system, etc.) Monitoring and control of nursery systems of vectors diseases and etiologic agents Co-ordination with municipalities, states, land owners and/or tenant farmers and environmental organisations on the quality of industrial and domestic effluents released to the river basin Public information and release of studies related to water quality

*Note: TO: time of occurrence. P: planning, C: construction, O: operation

TABLE III.2. HYDRO-ELECTRIC POWER PLANTS: IMPACTS ON THE BIOLOGICAL ENVIRONMENT

Environmental factor	Impacts	TO*	Measures/Actions/Projects/Programmes
Vegetation	Inundation of vegetation with loss of species Reduction of number of individuals, with loss of genetic material and commitment of flora in danger of extinction Interference with timber potential Loss of natural habitats and food availability to fauna Interference with conservation Increase of threat on the rest of vegetation in the neighbourhood of reservoir Interference with vegetation beyond the reservoir due to raise of ground water table and other phenomena	C/O	Establishment and/or complementation of germ-plasma bank Establishment and/or consolidation of conservation units Establishment of forest arboreta Re-establishing of vegetation of bordering areas Mechanisms that minimise the effects of rise of ground water table (construction of barriers, drainage, pumping , etc.) Incentive to owners for maintenance of remaining vegetation Scientific and cultural use of fauna Timber exploitation in the reservoir area Co-ordination with relevant organisations Public information related to vegetation
Aquatic fauna	Interference with the qualitative and quantitative composition of aquatic fauna with loss of genetic material and endangering fauna threatened by extinction Interference with the reproduction of species (interruption of migration, reproductive site extinction, etc.) Interference with conditions needed for fauna survival	C/O	Monitoring and handling of fauna Establishment of aquaculture stations for cultivation and repopulation of species Establishment of mechanisms for transposition of population and for cultivation and repopulation of species Establishment of protective measures to reproductive sites Establishment of centres for fauna protection Aquatic fauna rescue Scientific and cultural utilisation of fauna Co-ordination with relevant organisations Public information related to aquatic fauna
Terrestrial and winged fauna	Interference with the qualitative composition of terrestrial and winged fauna with loss of genetic material and endangering fauna threatened by extinction Migration caused by flood with increase of population in areas without that capacity to support the increase Increase of threat on the rest of fauna due to predatory fauna	C/O	Establishment or and/consolidation of conservation units Fauna rescue Creation and re-introduction of fauna Monitoring and handling of fauna Establishment of centres for fauna protection Control of predatory hunting Scientific and cultural utilisation of fauna Co-ordination with relevant organisations Public information related to terrestrial and winged fauna

*Note: TO: time of occurrence. P: planning, C: construction, O: operation

TABLE III.3. HYDRO-ELECTRIC POWER PLANTS: IMPACTS ON THE SOCIO-ECONOMIC AND CULTURAL ENVIRONMENT

Environmental factor	Impacts	TO*	Measures/Actions/Projects/Programmes
Population aspects: Urban	Inundation/interference with cities, towns and villages, etc. (habitations, improvements, social equipment, industrial and commercial organisations, etc.) Compulsory displacement of population Interference with the physical and territorial organisation Interference with the socio-cultural and political organisation Interference with the economic activities Increase of population movements (immigration & emigration) Demographic changes in population settlements near the site Appearance of population agglomerations Overload to social equipment and services (health, sanitation, education, safety, etc..)	P/C/O	Communication and negotiation with affected population Relocation of cities, towns and villages Population handling (resettlement, relocation compensation) Re-activation of affected economy Analysis and follow-up of population movements Co-ordination with municipalities aiming at an orderly growth Resizing of social equipment and services Establishment of criteria for the utilisation of local/regional manpower Monitoring of socio-economical and cultural activities
Population aspects: Rural	Inundation/interference with land, improvements, rural equipment and population Compulsory displacement of population Interference with the physical and territorial organisation Interference with the socio-cultural and political organisation Interference with the economic activities Increase of population movements (immigration and emigration)	P/C/O	Communication and negotiation with affected population Population handling (resettlement, relocation compensation) Relocation of rural settlements and isolated economical and social infrastructure Reorganisation of remaining proprieties Reactivation of affected economy Incentive to economical activities and establishment of social equipment in the resettlement projects(education, health, sanitation, technical assistance and so on) Analysis and monitoring of population movements
Agricultural sector	Alteration of economical activities (agriculture and stock raising, vegetal and mineral extracting, fishing activities) Loss of agricultural land Loss of forest and mineral resources Alteration of agrarian structure Loss of tax collection	P/C/O	Reorganisation of economic activities Reorganisation of remaining properties Fast exploitation of mineral and forest resources in the reservoir area Reorganisation of work structure

*Note: TO: time of occurrence. P: planning, C: construction, O: operation

(Table III.3 continued on next page)

TABLE III.3. HYDRO-ELECTRIC POWER PLANTS: IMPACTS ON THE SOCIO-ECONOMIC AND CULTURAL ENVIRONMENT (CONT.)

Environmental factor	Impacts	TO*	Measures/Actions/Projects/Programmes
Industrial sector	Interference with/closing of industries and/or production reduction due to alteration of raw material supply Loss of tax collection	P/C/O	Reorganisation of economical activities Alternative sources for supply of raw materials Reorganisation of work structure
Service sector	Interference with/discontinuation of commercial activities and services Alteration in demand and supply of services and commercial activities Alteration of price structure Decrease of tax collection	P/C/O	Redimensioning of commercial activities and services Reorganisation of work structure Reorganisation of economic activities
Public health and basic sanitation	Alteration of demand for health and sanitation services Dissemination of endemic diseases Proliferation of disease vectors Dissemination of diseases from outside the region Occurrence of accidents to population and workers Transport of organic and industrial sewage to reservoir	C/O	Monitoring of population health conditions Reorganisation of health services and basic sanitation Co-ordination with relevant organisations for prevention and control of diseases Co-ordination with relevant organisations for treatment and monitoring of organic and industrial sewage and garbage
Habitation	Alteration in the demand for habitation	C/O	Reorganisation of structure for habitation Reintegration of villages and residences Co-ordination with relevant organisations
Education	Alteration in the demand for education	C/O	Reorganisation of educational infrastructure Co-ordination with relevant organisations
Infrastructure	Interruption/discontinuation of communication system, roads, rail, airports, ports, transmission/distribution systems, ore transportation systems, etc.	C	Reorganisation of infrastructure Relocation of affected infrastructure (traffic system, communication, transmission and distribution) Co-ordination with relevant organisations
Indigenous peoples and other ethnic groups	Interference with indigenous peoples and/or other ethnic groups Alteration of socio-economical and cultural organisation Compulsory displacement of population groups Unbalance in the health conditions and nourishment	P/C/O	Negotiations with affected communities and relevant organisations on impacts and mitigating measures Negotiations with the national congress Agreements with affected groups and relevant organisations Monitoring and control of inter-ethnic contacts Territorial compensation Support and assistance to affected communities
Cultural heritage	Inundation of archaeological sites Loss of landscape Loss of buildings with cultural value Loss of speleological sites Interference with tourist potential Alteration of historical regional dynamics	C/O	Accelerated exploration of archaeological, historical, palaeontological, speleological sites Rescue of buildings with cultural value Reconstitution of pre-historic, historic and cultural memory Public information on cultural heritage (publications, museums, laboratories) Increase of cultural potential aiming at education and tourism

*Note: TO: time of occurrence. P: planning, C: construction, O: operation

TABLE III.4. TRANSMISSION LINES: IMPACTS ON THE PHYSICAL AND BIOLOGICAL ENVIRONMENT

Cause/activity	Impacts	TO*	USS*	RSS*	Measures/Actions/Projects/Programmes
Opening of right-of-way, construction of access roads, installations for erection of structures and cables, site works	Removal of vegetation	C	X	X	Selective clearing and appropriate pruning
	Soil erosion	C	X	X	Replanting the right-of-way with adequate vegetation
	Interference with water resources	C			Recovering of degraded areas
	Interference with fauna and flora	C/O	X	X	Implementation and strengthening of conservation units
	Interference with indigenous populations or other ethnic groups	C/O	X	X	Monitoring and inter-ethnic control Control of erosion processes
Erection of structures and installation of cables	Temporary damage to soil	C	X	X	Recovering of degraded areas
	Temporary damage to vegetation	C	X	X	Adaptation of construction criteria to the environmental conditions
Maintenance of right-of-way	Interference with fauna and flora	O	X	X	Selective clearing and appropriate pruning Replanting the right-of-way with adequate vegetation
Introduction of an artificial obstacle	Interference with the migratory route of birds	C/O	X	X	Adequate system of signals
Energising and operation of transmission lines Electro-magnetic effects	Biological effects on fauna and flora	O	X	X	Improvement of project criteria

*Notes:

TO: Time of occurrence. P: planning, C: construction, O: operation

USS: Urban Switching Station

RSS: Rural Switching Station

TABLE III.5. TRANSMISSION LINES: IMPACTS ON THE SOCIO-ECONOMIC ENVIRONMENT

Cause/activity	Impacts	TO*	USS*	RSS*	Measures/Actions/Projects/Programmes
Opening of right-of-way, construction of	Interference with indigenous				Support to indigenous peoples and other groups
access roads, installations for erection of	populations or other ethnic groups	P/C/O		X	Monitoring and inter-ethnic control
structures and cables, site works	Land expropriation				Multiple uses of the right-of-way
	Limitation of soil use due to	C	X	X	Resettlement of urban population
	right-of-way	C/O	X	X	Resettlement of economical and social
	Expectation of the affected				infrastructure
	population	P/C/O	X	X	Compensation for land and improvements
	Displacement of population				Social and environmental information
	Induced occupation on borders of	C/O	X	X	
	transmission lines and access roads				
	Interference with agriculture	C/O	X	X	
	Interference with buildings, public				
	roads and traffic	C/O	X	X	
	Interference with historical and				
	cultural sites	C/O	X		
		C/O	X	X	
Erection of structures and	Temporary damage to cultivated	C	X		Compensation for production losses
installations of cables	land.				
	Interference with indigenous				Support to indigenous peoples and other groups
	populations or other ethnic groups	C	X		Monitoring and inter-ethnic control
Transport of heavy equipment	Damage to access roads	C	X	X	Selection of appropriate roads for equipment transport/traffic
	Interference with traffic	C	X	X	orientation
Introduction of an artificial obstacle	Landscape degradation				Improvement of project criteria
	Scenery disorder	C/O	X	X	
	Lack of visual integration				
Energising and operation of transmission	Biological effects	O	X	X	Improvement of project criteria
line	Audible noise, radio and TV	O	X	X	Public information on social and environmental matters
Electro-magnetic effects	interference				
Occupation of right-of-way	Interference with transmission				Organise multiple use of right-of-way
	line	O	X		
	Garbage and waste disposal	O	X		
	Risk of accidents	C/O	X	X	

*Notes:

TO: Time of occurrence. P: planning, C: construction, O: operation

USS: Urban Switching Station; RSS: Rural Switching Station

TABLE III.6. SWITCHING STATIONS: IMPACTS ON THE PHYSICAL AND BIOLOGICAL ENVIRONMENT

Cause/activity	Impacts	TO*	USS*	RSS*	Measures/Actions/Projects/Programmes
Occupation of area for switching stations and civil works (land clearance, earthworks and site preparation) neutral conductor Construction of access roads	Removal of vegetation cover Interference with fauna and flora Interference with water resources Interference with protected areas Boundary effect	C C C C/O C/O	X X	X X X X X	Recovering of degraded areas Implementation of conservation (special protection areas) Protection of water resources Control of erosion processes Studies of flora and fauna
Operation of switching stations (liquid and solid waste, water intake)	Interference with fauna and flora Pollution of water resources	O O	X X	X X	Fauna and flora management Protection of water resources
Energising and operation of switching stations. Electro-magnetic effects	Biological effects on fauna and flora	O	X	X	Improvement of project criteria

*Notes:

TO: Time of occurrence. P: planning, C: construction, O: operation

USS: Urban Switching Station

RSS: Rural Switching Station

TABLE III.7. SWITCHING STATIONS: IMPACTS ON THE SOCIO-ECONOMIC ENVIRONMENT

Cause/activity	Impacts	TO*	USS*	RSS*	Measures/Actions/Projects/Programmes
Occupation of area for switching stations and civil works (deforestation and site preparation),neutral conductor Construction of access roads	Interference with indigenous populations or other ethnic groups	P/C/O		X	Support to indigenous communities and ethnic groups Monitoring and inter-ethnic control Enlargement of urban services and social equipment Basic sanitation and health programmes Resettlement of population Resettlement of economical and social infrastructure Compensation for land and improvements Rescue of cultural heritage (of archaeological, historical and landscape value) Social and environmental information
	Interference with social equipment and community areas, historical and cultural sites	C/O	X	X	
	Displacement of population	P/C	X	X	
	Increase of migration due to increase of work opportunity	C	X	X	
	Improvement of local economy followed by economic deterioration after work is finished	C/O	X	X	
	Interference with health of population	C	X	X	
	Interference with agriculture	C		X	
	Noise, particulate material	C	X	X	
Energising and operation of switching stations.	Audible noise, radio and TV interference	O	X	X	Improvement of project criteria Planting trees for the absorption of noise Control of effects caused by electromagnetic fields Treatment and final waste disposal Public information on social and environmental matters
Electro-magnetic effects	Biological effects	O	X	X	
Release of liquid and solid waste	Spread of diseases due to sewage discharge	O	X	X	
Transport of heavy equipment	Damage to roads	C	X	X	Selection of adequate roads for the transport of of heavy equipment/traffic orientation
Introduction of an artificial obstacle	Landscape degradation Scenery disorder Lack of visual integration	C/O	X	X	Planting trees to decrease the visual impact Landscape improvement projects
Handling of dangerous material	Health damage	C/O	X	X	Implementation of relevant mechanisms for waste treatment and final disposal

*Notes:

TO: Time of occurrence. P: planning, C: construction, O: operation
USS: Urban Switching Station
RSS: Rural Switching Station

TABLE III.8. CONVENTIONAL THERMAL POWER PLANTS: SOCIO-ECONOMIC IMPACTS

Cause	Impacts	Fuel Type*					TO*	Measures/Actions/projects/Programmes
		C	DO	FO	NG	BM		
Particulate emissions to atmosphere	Depending on concentration: - respiratory problems - interference with fauna and flora - undesirable aesthetic effect	X		X		X	O	Utilisation of fuel with lower inert material content Removal of inert material before combustion Removal of inert material after combustion (filters) Dispersion with adequate chimneys Utilisation of modern combustion technologies with higher efficiencies (FB combustion, combined cycle, co-generation) Monitoring emissions, air, rain and water quality, and meteorological conditions
SO_2 emissions to atmosphere	Depending on concentration: - irritating smell - respiratory and cardio-pulmonary problems - interference with fauna and flora - attack to different materials - rain acidification	X	X	X	X	X	O	Utilisation of fuel with lower sulphur content Removal of sulphur before, during or after combustion Dispersion with adequate chimneys Utilisation of high efficiency technologies (FB combustion, combined cycle, co-generation) Monitoring emissions, air, rain and water quality, and meteorological conditions
Emissions of NO_x, hydrocarbons and carbon monoxide to atmosphere	Depending on concentration: - production of photo-chemical oxidisers - decrease of visibility (smog) - irritation of eyes and throat - interference with fauna and flora - rain acidification	X	X	X	X	X	O	Combustion control Utilisation of a system for tangential burning Utilisation of low NO_x burners Dispersion with adequate chimneys Utilisation of high efficiency technologies (FB combustion, combined cycle, co-generation) Monitoring emissions, air, rain and water quality, and meteorological conditions
CO_2 emissions to atmosphere	Contribution to climate change and global warming	X	X	X	X	X	O	Planting trees for carbon fixation Utilisation of high efficiency technologies (FB combustion, combined cycle, co-generation)
Leakage during handling and storage of liquid fuel	- contamination of water bodies - interference with fauna and flora	X	X	X		X	O	System for oil containment Impermeabilisation of storage area

*Notes:

Fuel C: mineral coal, DO: diesel oil, FO: fuel oil, NG: natural gas, BM: biomass

TO: time of occurrence. P: planning, C: construction, O: operation, PO: Post-operation

(Table III.8 continued on next page)

TABLE III.8. CONVENTIONAL THERMAL POWER PLANTS: SOCIO-ECONOMIC IMPACTS (CONT)

Cause	Impacts	Fuel Type*					TO*	Measures/Actions/projects/Programmes
		C	DO	FO	NG	BM		
Sanitary effluents	- dissemination of diseases - decrease of soluble oxygen in receptor body - interference with fauna and flora	X	X	X	X	X	O/C	These effluents should be treated separately from the other liquid effluents from the plant Utilisation of compact systems for treatment of sanitary sewers
Percolation of rain water in the areas used for fuel storage	- contamination of water bodies with leached metals which are solid, suspended and dissolved and pH alteration - contamination of ground water table	X				X	O	Sedimentation and decantation basins Effluent neutralisation Chemical precipitation of dissolved metals Impermeabilisation of storage area Monitoring of ground water plate
Cooling water	Depending on technology used: <u>Open system</u>: - increase of water temperature in the water receptor body; - reduction of dissolved oxygen - interference with fauna and flora <u>Closed system/humid cooling tower:</u> - chemically active mist (biocides and anti-corrosive agents) - decrease of visibility - interaction of the humid mist with the plume of chimney (causes acidification of atmosphere) <u>Closed system/dry cooling tower:</u> - smaller impacts on atmospheric and water resources	X	X	X	X	X	O	Studies of thermal dispersion in water body. Evaluation of impact on aquatic ecosystem Monitoring of ichthyofauna Utilisation of cooling towers with demisters Siting of cooling towers taking into consideration prevailing winds in the region Avoid superposition of mist and plume Utilisation of chemical additives in the cooling water in minimum possible concentrations Verification of aerodynamic interference of cooling tower with dispersion conditions of plume of chimney
Noise	- noise pollution	X	X	X	X	X	O	Plant trees for noise absorption Project criteria for noise absorption Noise monitoring
Aesthetical distortions	- visual pollution	X	X	X	X	X	C/O	Reduction of visual impact
Liquid effluents from the heavy ash removal system	- contamination of water bodies with suspended and dissolved solids, leached metals and pH alteration							Closed loop with recirculation Decanters and sedimentation basins pH correction and precipitation of metals Utilisation of dry system for ash removal Monitoring of water quality

*Notes:

Fuel C: mineral coal, DO: diesel oil, FO: fuel oil, NG: natural gas, BM: biomass

TO: time of occurrence. P: planning, C: construction, O: operation, PO: post-operation

(Table III.8 continued on next page)

TABLE III.8. CONVENTIONAL THERMAL POWER PLANTS: SOCIO-ECONOMIC IMPACTS (CONT)

Cause	Impacts	Fuel Type*					TO*	Measures/Actions/projects/Programmes
		C	DO	FO	NG	BM		
Liquid effluents from rain water drainage, wash water treatment and purging process	- increase of the content of suspended and dissolved solids - interference with fauna and flora	X	X	X	X	X	O	Closed systems for solid fuel and ash handling Operational care to avoid the spread of fuel, particulates and ashes in the plant courtyard Sedimentation and neutralisation basins Monitoring of liquid effluents
Solid wastes from the process	- undesirable aesthetical effect - occupation of large areas for deposit - possibility of contamination of water resources due to rain water percolation - dust and particulates	X		X		X	O/PO	Utilisation of solid wastes as raw material for industrial processes Return of material to mine pits for topographic reconstitution of coal mined areas Selection of areas for waste disposal Implementing of places filled up with earth according to environmental guidelines Monitoring of rain water draining and leached material. Tree belt for protection against winds
Migratory movements caused by the plant	- increase of demand for public services, dwelling and transport infrastructure - alteration in the socio-cultural and political organisation of the region - increase of economic activities of the region and possible decrease after finishing of plant	X	X	X	X	X	O	Master regional developing plan Support to municipalities Adaptation of habitation and transport infra-structure Institutional management Reorganisation of economic activities Basic health and sanitation organisation
Occupation of site area (clearing and earth works)	- interference with population - interference with flora and fauna - noise and dust - soil erosion - soil use alteration	X	X	X	X	X	O	Monetary compensation or exchange of areas Recovering of degraded areas Tree planting Use of anti-dust systems
Transport of heavy equipment	- noise - local transit perturbation	X	X	X	X	X	O	Planning of traffic system use to avoid peak times
Solid wastes, filters, clothes, sludge	- interference with flora and fauna - interference with public health - risk of fire	X	X	X	X	X	O	Adequate treatment of solid wastes

*Notes:

Fuel C: mineral coal, DO: diesel oil, FO: fuel oil, NG: natural gas, BM: biomass

TO: time of occurrence. P: planning, C: construction, O: operation, PO: post-operation

TABLE III.9. NUCLEAR POWER PLANTS: SOCIO-ECONOMIC IMPACTS IN NORMAL OPERATION

Causes	Impacts	TO*	Measures/Actions/Projects/Programmes
Emissions of radioactive gases to atmosphere	internal and external doses (non-detectable biological effects)	O	Filtering and radioactive decay Dispersion in favourable atmospheric conditions Optimal dimensioning of chimney Implementing of design measures, operational procedures and programmes to minimise effluents Continuous control and monitoring systems of emissions
Radioactive liquid effluents	internal and external doses (non detectable biological effects)	O	Filtering Radioactive decay Removal by ionic exchange evaporation/condensation Solidification Dispersion in aquatic environment under appropriate conditions Implementing of design measures and operational procedures to minimise effluents Continuous control and monitoring systems of emissions
Solid radioactive wastes with low and medium activities (temporary waste storage for solid radioactive wastes)	external doses (non detectable biological effects)	O/PO	Solidification, compacting and confinement in special containers Storage in special licensed deposits Implementation of design measures, operational programmes and procedures for waste minimisation Environmental and radiological monitoring
Aesthetical distortion	Visual pollution	C/O	Landscape and architectural enhancement
Water cooling systems	Depending on the technology: <u>Open system:</u> - increase of water temperature in the water receptor body - reduction of dissolved oxygen - interference with aquatic fauna and flora <u>Closed system/humid cooling tower:</u> - chemically active mist (biocides and anti-corrosive agents) - decrease of visibility <u>Closed system/dry cooling tower:</u> - smaller impacts on atmospheric and water resources	O	Studies of thermal dispersion in water body. Evaluation of impacts on aquatic ecosystem Monitoring of ecosystem Utilisation of cooling towers with demisters Siting of cooling towers taking into consideration prevailing winds in the region Verification of aerodynamic interference of cooling tower with dispersion conditions of plume of chimney
Sanitary effluents	- dissemination of diseases - decrease of soluble oxygen in receptor body - interference with fauna and flora	C/O	Treatment of sanitary sewers separated from treatment of other liquid effluents

*Notes:
TO: time of occurrence. P: planning, C: construction, O: operation, PO: post-operation

(Table III.9 continued on next page)

TABLE III.9. NUCLEAR POWER PLANTS: SOCIO-ECONOMIC IMPACTS IN NORMAL OPERATION (CONT.)

Causes	Impacts	TO*	Measures/Actions/Projects/Programmes
Migratory movements caused by the plant	- increase of demand for public services, habitation and transport infrastructure - alteration in the socio-cultural and political organisation of the region - increase of the economic activities of the region and their possible decrease after finishing of plant	C/O	Master regional developing plan Support to municipalities Adaptation of habitation and transport infrastructure Institutional management Reorganisation of economical activities Basic health and sanitation organisation
Occupation of site area (clearing and earth works)	- interference with population - interference with flora and fauna - noise and dust - soil erosion; soil use alteration	C	Monetary compensation or exchange of areas Recovering of degraded areas Planting of trees to absorb noise Use of dust retention systems
Transport of heavy equipment	- noise - local transit perturbation	C	Planning of traffic system to avoid peak times
Noise	- noise pollution	C/O	Project conception for noise reduction

*Notes:
TO: time of occurrence. P: planning, C: construction, O: operation, PO: post-operation

TABLE III.10. NUCLEAR POWER PLANTS: SOCIO-ECONOMIC IMPACTS IN ACCIDENT SITUATIONS

Causes	Impacts	TO*	Measures/Actions/Projects/Programmes
Emissions to atmosphere of radioactive gases and aerosols	- internal doses (inhalation and ingestion) above limits - contamination of food, water resources and air - external doses above limits - contamination of soil and air	O	Probabilistic safety analysis, risk/consequences analysis Containment within the plant Utilisation of processes for filtering and radioactive decay Systems for continuous emission control and monitoring Planning of emergency actions for prevention, mitigation, etc. (Emergency Response Plan)
Radioactive liquid effluents	- internal doses (ingestion) above limits - contamination of animals, plants and water resources - external doses above limits - contamination of water bodies	O	Probabilistic safety analysis, risk/consequences analysis Containment and recirculation Utilisation of processes for filtering and radioactive decay Systems for continuous emission control and monitoring Planning of emergency actions for prevention, mitigation, etc. (Emergency Response Plan)

*Notes:

TO: time of occurrence. P: planning, C: construction, O: operation, PO: post-operation

III.4. Full energy chain impacts

The previous sections of this annex dealt with only those impacts arising from the production of electricity (i.e. power plant and transmission). In this section, a brief description is given of the impacts associated with the full energy chain (FENCH) for the principal energy sources and generation technologies. The primary purpose of this description is to illustrate the wide range of waste streams and emissions that need to be considered in the comparative assessment framework, their basic characteristics and their approximate magnitudes. Estimates of magnitude are, however, very approximate. Furthermore, the waste arisings and emissions per unit of electricity production can be reduced significantly through improved operational practices.

As already highlighted in the previous sections, a large number of energy chains (fossil, nuclear, hydro, other renewable energies) and technology options exist, each producing a range of waste streams and socio-economic effects. Some of the wastes may be of a nature, or at levels low enough, that they are not considered harmful, and therefore are discharged directly to air or to surface water bodies. These are referred to here as *direct emission wastes*. Other wastes arise as solids that cannot be discharged directly. Others may contain hazardous substances at concentrations high enough to require some treatment for their safe management and special systems for their safe disposal. This treatment may result in further discharges to air or surface water bodies and the production of other solid wastes. These wastes are referred to here as *non-emission wastes*.

III.4.1. Coal chains

III.4.1.1. Coal mining

Coal can be mined, according to its geological setting by a variety of methods, the most common of which are underground mining (room and pillar or long-wall techniques) and surface mining (area or contour strip mining). Both underground and surface mining can cause land disturbances resulting in negative effects on the surrounding environment. Land reclamation is needed to mitigate these effects and recover degraded areas. The large excavations associated with surface mining, as well as the deposition sites for the large amounts of ‘overburden’ removed in order to gain access to the coal deposit, can cause dramatic changes to the landscape. Underground coal extraction also can cause significant impacts on the landscape, in particular through land subsidence in some cases. The degree of difficulty and the time required for the impacted land to be restored depend to a large extent on the physical and topographical conditions of the site (e.g. amount of recontouring that has to be done to the land), the fertility of the soil (e.g. amount of fertiliser that has to be added), the amount and type of planting and reseeding required, and the amount of rainfall in the area. In some cases, the difficulties and costs of land restoration are greater for underground mining than for surface mining, in particular when extensive surface subsidence has occurred.

Both methods of mining can have impacts also on streams and water bodies in the surrounding areas, caused by the drainage of polluted water from the mines. All coals contain some concentration of soluble minerals, that may be leached into waters draining from the mine into water bodies, thereby causing degradation of the water quality. Measures taken to minimise the detrimental effects of mine drainage include: drainage control in the mine area; proper disposal to ensure that sulphur-bearing pyritic materials do not come in contact with water; sealing up abandoned mines to avoid leaching and drainage; and chemical treatment of acid mine drainage (alkaline neutralising agents).

Coal mining has a number of occupational hazards. In addition to the risks of accidents in underground mines (fires, explosions, mine collapse, etc.) and in surface mines (accidents with mining machinery, wall collapse, etc.), coal miners are subject to respiratory diseases, especially pneumoconiosis, commonly known as ‘black-lung’ disease. Coal miners may be exposed also to an increased level of radiation exposure, arising from natural radioactive materials (mainly radon) that are released from the coal and rock during mining operations. In many countries, stringent control measures have considerably reduced exposures to radiation and to the dust precursors of black-lung disease. Another occupational hazard in coal mining arises from the high levels of noise produced by mining equipment.

Mining is also a source of methane gas, which is present in significant quantities in many coal seams and is released during mining. In underground mines, methane and dust pose risks of explosions. Also, the mining related emission of methane is a contributor to the atmospheric build-up of greenhouse gases (GHGs) arising from human activities. There are, however, possibilities to reduce methane emissions from coal mines by using methane recovery techniques.

III.4.1.2. Coal cleaning and processing

Coal cleaning is accomplished by physically separating ash and sulphur-bearing pyritic material from coal (chemically bound organic sulphur is not removed). These physical beneficiation techniques are capable of removing up to 50% of the sulphur and 75% of the ash contained in the raw coal. The amount of pollution generated in the process of coal cleaning depends upon the amount of coal treated and the chemical and physical properties of the coal. Most air pollution arising from coal washing is the result of drying the coal in a stream of hot gas. The air pollutants are fine coal dust, ash, NO_x and SO_x, resulting from the combustion of the coal used to supply the hot gases for coal drying. In addition, dust is created during crushing and grinding of the coal. Air pollution can arise also from refuse pile fires, which can occur as the result of spontaneous combustion. Coal washing requires large amounts of water, the quantity depending upon the type of coal and the process used. The liquid effluent produced, commonly called 'black-water', contains suspended small particles of coal and other solids. Black-water usually is sent to a 'tailings pond' where the solids are allowed to settle and the clarified water is recirculated to the washing process. Solid wastes from coal cleaning and processing consist of coarse and fine solids, that usually contain sulphur-bearing pyritic compounds and other chemicals, and that constitute a potential source of acid mine drainage.

III.4.1.3. Coal transportation

Coal is transported by rail, road, waterways (rivers, canals, lakes, inter-coastal waterways and oceans), slurry pipelines and conveyer belts. Transport related environmental impacts occur during loading, conveyance and unloading of coal. The impacts affect natural systems (including agriculture, forestry, horticulture and aquaculture), buildings and installations, and humans.

Engines powering the transportation system cause noise and lead to pollutant emissions to the air. In addition, there are inevitably some accidents involving coal transportation vehicles (trains, trucks, barges, ships), that can cause injury, death, damage to other facilities and environmental impacts.

The transport of coal in all its forms involves unavoidable 'fugitive dusts' (coal lost to the air in the form of small particles), even when preventive measures are taken. For rail transport, it is estimated that about 25% of the total coal dust loss occurs during loading, 50% during transit, and 25% during unloading. In addition to fugitive dust, there is some coal loss due to spillage. Some estimates suggest that the fugitive dust amounts to about 0.2 kg/t of coal loaded, and a similar amount during unloading. Coal transport by rail has a number of other environmental impacts relating to noise (engine, exhaust, horn, wheel-rail interaction and brake cooling blowers). Diesel engines emit exhaust gases and some chemicals may be leached from the coal through exposure to rainfall during transit. Sparks from trains may cause brush fires, mainly along the rail right-of-way, but potentially spreading to surrounding areas. Control measures involve spraying vegetation along the right-of-way with chemicals.

Truck transport, usually confined to short distance haulage, involves exhaust emissions, coal spillage and fugitive dust losses (estimated at 0.04% of the load during loading and unloading combined and 0.05% during transit). Near the road, noise from trucks can exceed 100 dB. Heavily laden coal trucks can cause structural damage to roads and bridges.

The transport of coal by water involves towed barges, motorised barges and ships. Losses during loading, unloading and transit are similar to those for truck and train transport.

Slurry pipelines with electrically powered pumping stations 100-160 km apart are used in some cases for transporting coal in a water-based suspension. With this system, there are no fugitive dust losses and, with effective sound insulation and remote siting, noise usually is not a problem.

However, large quantities of water are needed for preparing the slurry, and normally it is not economical to return the water for reuse. Thus, water consumption can have an adverse impact on the supplying water body (river or lake). Also, the slurry has to be 'dewatered' prior to combustion in the power plant. The effluent from the dewatering process contains coal particles and saline compounds, and is a potential source of environmental impacts.

III.4.1.4. Coal storage

The storage of coal can present problems of spontaneous combustion, especially in the case of lower rank coals with high content of volatile compounds. Special preventive precautions should be taken.

III.4.1.5. Summary of impacts from the coal chain

The major components of the fuel chain associated with the direct combustion of coal are listed in Table III.11. For each fuel chain component, this table presents also the major air and water emissions, descriptions of the other waste streams, and estimates of the approximate magnitude of these wastes. The solid waste quantities have been estimated based on a coal with a density of 6,600 kg/m^3, a heat content of 8,000 kWh/t, an ash content of 7% by weight, and a sulphur content of about 1% by weight. The qualities of coal in terms of heat output per tonne or amounts of ash and other wastes vary considerably. For example, lignite has a lower heat value and contains significantly more ash than hard coal. Therefore, the quantities of waste presented in Table III.11 are approximate and should be considered only as indicative.

The amounts of solid wastes will be influenced also by the type and efficiency of installed flue gas treatment systems. For example, the use of limestone injected into the combustion chamber as a means for removing sulphur increases the emissions of CO_2 and almost doubles (500,000 t/a versus 300,000 t/a) the quantity of solid wastes, relative to a plant equipped with a wet flue gas scrubbing system for sulphur control. In addition, the toxic components of the ash (metals, radionuclides, etc.) are incorporated in the total solid waste volume from the plant using limestone injection, whereas in a plant equipped with wet scrubbers, the solid wastes from the FGD process are essentially free of these constituents. This may affect the choice of systems for the management and disposal of the solid wastes.

III.4.2. Oil and natural gas chains

Residual fuel oil, a by-product of the petroleum industry, can be used as boiler fuels in thermal plants for electricity production, but it has other energy applications also. With a carbon to energy ratio that is less than half that of coal, and about two-thirds that of oil, natural gas may receive strong attention as a fuel for generating electricity when there is need to minimise CO_2 emissions. So far as the greenhouse effect is concerned, this advantage may be cancelled by releases of methane occurring during gas extraction, transportation and handling. This illustrates the need to consider the full energy chain, bearing in mind also that options exist for reducing such methane losses.

The impacts from the oil and natural gas chains for electricity generation are associated with the overall activities for oil and gas exploration, production, processing and transportation, as described below.

III.4.2.1. Oil and natural gas production

Exploration and production of oil and natural gas, whether carried out onshore or offshore, have a number of environmental impacts. Accidents and equipment failures can cause harm to workers and the environment. Fires, explosions and accidental oil spills are the most common accidents.

Offshore oil and gas exploration and production is a major industrial development. The support it needs in terms of technologies and specialised personnel is large and is provided from coastal areas as near as possible to the production field. In developing countries, labour and housing shortages may become acute, and considerable pressure is put on social and other community services. The siting of the necessary facilities, such as pipeline terminals and platform construction sites, leads to some problems in land management, since it competes with other possible uses for the coastal zone (fishery, tourism, etc.).

Although accidental spills from offshore operations normally are of relatively small volumes, some large spills have occurred in the past. Even with careful treatment of effluent discharges and stringent controls to minimise accidental oil spillage, both onshore and offshore oil and gas production result in some discharge to the surrounding environment. Tidal marshes, coastal wetlands, rivers, swamps and sheltered bays typically are sensitive ecosystems that support a variety of organisms at all stages of development, and even low levels of hydrocarbon pollution may have serious ecological impacts.

The trend is towards working at greater depths and harsher environments than those of the North Sea and there may be a possibility that higher environmental risks may occur in these conditions than have been experienced in the past.

Crude oil frequently is associated with large amounts of emulsified brine. After separation, the brine usually is disposed of by reinjection into the earth. However, some brine may be discharged to marine or terrestrial water bodies, which can have serious effects on aquatic ecosystems.

During natural gas extraction, there are some leaks. Natural gas is mainly methane, a strong greenhouse gases, and there are some concerns that gas leakage can add to the possible risks of global warming.

III.4.2.2. Oil transportation

Marine oil tankers are the most important means of international oil transportation. Accidents with oil tankers can have serious effects upon the environment and marine life, including serious and long term damage to important industries such as fisheries and tourism. Winds and current can move oil for long distances in a relatively short time, and the consequences of a major spillage can be spread over a large area. Another danger to oceans and coastal ecosystems results from the oil discharged during the cleaning of oil tankers after unloading. Some tankers are filled with water as ballast after the oil is unloaded, and the ballast water becomes contaminated with oily residues. The discharge of oil contaminated ballast water, before taking on a new cargo of oil, adds to oil pollution of the oceans. The oil industry has introduced a variety of methods, such as using crude oil instead of water for tanker cleaning, to mitigate such ‘operational pollution’.

Oil terminals often are constructed within or near ecologically sensitive coastal areas, such as estuaries, which provide valuable nursery grounds for fisheries and other aquatic wildlife. There always exists a risk of oil spillage during the transfer of oil from the tanker to the shore facility. Even in the absence of large scale oil spills, the cumulative effect of many small spills and leaks remains.

Because oil floats on the sea surface, spilled oil tends to become deposited in the intertidal zone near or on the shoreline, causing many undesirable consequences, including damage to the aesthetic and recreational values of beaches. Suitable surface treatment agents can be used for the protection of shorelines from oil spills. When ecologically sensitive areas are threatened, emulsifying agents can be used to disperse the oil in the water.

With pipeline transportation, oil spills and fires can occur, with the most important initiating cause being damage to the pipeline. Pipelines on surface can cause disturbances to wildlife and to land use in certain areas.

III.4.2.3. Natural gas transportation

Natural gas consists of methane and other hydrocarbon compounds, and usually is transported in gaseous form through pipelines. The primary risks with gas pipelines are associated with fires and explosions, in particular for pipelines passing through or near heavily populated areas. In addition, pipeline leakage of methane, a strong greenhouse gas, contribute to the potential risks of climate change and global warming.

For ocean transport, natural gas is cooled to its liquid state (liquefied natural gas - LNG) for transport by special LNG tankers. The main environmental effects associated with natural gas liquefaction plants are the discharge of heat to the atmosphere or to fresh or marine waters, depending on the type of cooling system used, and the occasional emission or flaring of some components extracted during gas liquefaction. There is also a possibility of destructive evaporation of LNG if it comes in contact with water.

III.4.2.4. Oil processing (refining)

Refineries are large industrial installations with air and water emissions, large water requirements for processing and cooling, and risks of explosions and fires. The principal types of airborne emissions are volatile hydrocarbons, sulphur oxides, nitrogen oxides and particulates. Some amounts of carbon monoxide, volatile organic compounds and ammonia are emitted also. Liquid effluents contain chlorides, grease, ammonia nitrate, phosphate, suspended solids, dissolved solids and trace metals (Cr, Pb, Zn, Cu).

Refineries require large amounts of water, mainly for cooling and various process operations. Each process operation has different water usage and waste water characteristics associated with it. In addition to process waste waters, ballast water in tanks, storm water runoff and sanitary wastes contribute to the total waste load that must be treated before discharge to the environment. The most significant pollutants present in this waste load are oil and grease, phenols, ammonia, suspended and dissolved solids, sulphites and chromium. Treatment techniques consist mainly of primary separation of oil and solids and neutralisation, followed by biological treatment using activated sludge systems, aerated lagoons or oxidation ponds.

Unpleasant odour is another potential nuisance in and around refineries. Hydrogen sulphide (H_2S) and mercaptans are the principal malodorous compounds. Even small leakage of these compounds from a refinery can cause unpleasant smells in the surrounding area.

Accidental spills of stored crude oil or refined products can cause severe local environmental impacts, requiring extensive restoration efforts.

III.4.2.5. Summary of impacts from the oil and natural gas chains

The major components of the residual oil fuel chain are listed in Table III.12. For each fuel chain component, this table presents also the major air and water emissions, descriptions of the other waste streams, and estimates of the approximate magnitude of these wastes. Quantitative estimates for solid wastes are based on a power plant with 38% conversion efficiency, fired with residual fuel oil produced from a crude oil having an energy content of 1.4×10^6 kWh/m^3.

The major components of the natural gas fuel chain for electricity production are listed in Table III.13, together with the major air and water emissions and descriptions of the other waste streams for each fuel cycle component.

III.4.3. Nuclear energy chain

The nuclear energy chain includes a number of steps, that vary according to the reactor technology - i.e. light water reactor (LWR) or heavy water reactor (HWR) - and the type of spent fuel management option chosen - i.e. direct disposal (open cycle) or reprocessing and recycle (closed cycle). Light water reactors, including pressurised water reactors (PWRs) and boiling water reactors (BWRs), account for 85% of the nuclear capacity in operation and 80% of the capacity under construction world-wide. Therefore, the following sections focus on the discussion of the energy chain for LWRs.

At each step of the nuclear chain, different industrial processes have been deployed and the characteristics of facilities can differ significantly from country to country and, in the same country, from operator to operator.

The main steps of the overall nuclear fuel chain are:

- Uranium exploration, mining and milling;
- Conversion to uranium dioxide or hexafluoride (for LWR only);

- Enrichment (for LWR only);
- Fuel fabrication;
- Heavy water production (for HWR only);
- Electricity generation (nuclear power plant);
- Spent fuel storage;
- Spent fuel disposal (open cycle only);
- Reprocessing (closed cycle only); and
- Radioactive waste management and disposal.

The nuclear chain includes also transportation of fuel, in its various forms, from one step to the next and transportation of some wastes from their point of arising to the disposal site.

Social, health and environmental impacts of nuclear power plants, uranium mines and fuel cycle facilities arise from a number of causes, including both conventional and specifically nuclear activities. The impacts arising from conventional activities (e.g. mining, materials processing, transportation) are similar in type to those from other industrial activities; however, owing to the high energy content of nuclear fuel, the relative magnitude of the impacts, expressed in damage per unit of electricity generated, tends to be much smaller for nuclear power than for fossil fuelled generation. The specifically nuclear related impacts arise mainly from: the release of very small amounts of radioactive materials to air and water; the management and disposal of spent fuel and radioactive wastes; and risks associated with low probability, high consequence nuclear accidents (see Annex V).

A number of published studies on nuclear chain impact assessment provide estimates of the overall social, health and environmental effects resulting from nuclear electricity generation. However, it should be stressed that, like for other electricity generation chains, the magnitude and to some extent the types of impacts are highly dependent on technology and site specific characteristics. Therefore, the information provided below is essentially qualitative and should be considered as indicative only. As noted in other parts of this book, a comprehensive decision support study requires that a detailed environmental impact assessment (EIA) should be carried out based upon case and site specific data and information.

The levels of radioactivity emitted to air and water are strictly regulated, closely monitored and maintained below authorised limits set up by national or local authorities, in accordance with recommendations of the International Commission on Radiological Protection (ICRP). According to the ICRP recommendations [7, 8], radioactive emissions should be kept below levels that would cause harm to human health or the environment, and should be even lower than the emission limits authorised whenever the cost of achieving the reduction is lower than the estimated benefit of the corresponding impact reduction. This latter guideline is referred to as the ‘as low as reasonably achievable’ (ALARA) principle. The radiation protection limits that have been set up to protect humans are more than adequate to protect other living creature and the environment protection.

The potential health impacts resulting from radiation releases from nuclear facilities are, in most cases, not measurable since the resulting radiation doses generally are far below the doses received from natural background radioactivity. Therefore, the potential impacts resulting from such low level radiation releases can be estimated only through the application of theoretical dose-effect relationships. The doses caused by nuclear facility radiation releases are monitored and assessed by the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR). The 1994 report of this Committee [9] states that the collective effective dose committed to the world population by a 50-year period of operation of nuclear facilities (i.e. nuclear power plants, nuclear fuel cycle facilities and uranium mines) is 2 million man-Sieverts (man-Sv), as compared to 650 million man-Sv committed by natural radiation and 165 million man-Sv committed by radiation exposures (e.g. X ray analyses and radio-therapy) in medical diagnosis and treatment.

III.4.3.1. Uranium exploration, mining and milling

Uranium is widely distributed in nature and is present in most rocks, soils, rivers and oceans. Uranium exploration methods include classic techniques used for all minerals and specific techniques based upon radiation detection, taking advantage of the low radioactivity of uranium bearing ore bodies. Uranium exploration has little, if any, social, health or environmental impact when expressed in terms of effect per unit of electricity produced by nuclear power.

Economically recoverable uranium ore bodies - i.e. with uranium concentration ranging from some 500 ppm to more than 10% - are exploited in underground or open pit mines. Uranium is extracted also from some low grade deposits by in situ leaching and recovered as a by-product from copper, gold and silver mines and from phosphoric acid production.

The mined uranium ore is processed in milling plants, generally located close to the mines. Mechanical treatment (crushing and grinding) and chemical operations (acid or alkaline leaching) are used to extract, concentrate and purify the uranium. The product, referred to as 'yellow cake', contains uranium at a concentration of around 70% by weight.

Mining and milling operations generate atmospheric emissions (particles and radioactive gases), liquid releases and solid wastes that have a level of radioactivity falling within the lower range of natural background radioactivity. Solid wastes from underground mining (i.e. ore gangue), and milling (i.e. mill tailings), generally are backfilled into the mine excavations after their decommissioning. Overburden (i.e. earth and rock) removed during surface mining operations is used as cover when rehabilitating the mining and milling sites. The radioactivity levels of atmospheric emissions and liquid effluents are monitored and controls ensure that they remain below authorised levels.

The most significant impacts of mining and milling activities are occupational health effects resulting from accidents in mines and exposure of mine workers to radiation and dust. Radioactive emissions from the mining and milling facilities increase slightly the background natural radioactivity and might induce health impacts (additional risk of cancer) to the local and global population. As noted above, estimations of these low-dose effects can be made only through the use of theoretical dose-effect relationships. However, the actual impacts are impossible to measure, owing to the very low doses in comparison to the natural background doses and to the statistical variations in cancer occurrence rates within any given sample of population.

III.4.3.2. Uranium conversion

Conversion includes a sequence of physical and chemical processes required to convert the yellow cake into uranium hexaflouride (UF_6) for feeding to uranium enrichment plants or into uranium oxide (UO_2) for feeding to nuclear fuel fabrication plants. Different conversion technologies are used, depending on the end product required and on the processes that have been implemented in each country.

Radioactive emissions and residuals from conversion facilities are controlled and monitored, and their potential health impacts (estimated by dose-effect relationships) are not significant. Non-radiological occupational health effects result from the exposure of workers to toxic chemicals, in particular fluorine compounds, and to normal industrial facility accidents.

III.4.3.3. Uranium enrichment

In natural uranium the fissile isotope ^{235}U is present at a concentration of about 0.71% by weight. The enrichment process 'enriches' the ^{235}U concentration to the level of some 3-4% that is required for fuelling light water reactors (heavy water reactors are fuelled with natural uranium). Two enrichment processes have been industrially deployed: gaseous diffusion and gaseous centrifugation. In both processes, the occupational and public health impacts are low.

The enrichment process consumes electricity, with the electricity requirements being significantly higher with gaseous diffusion than with centrifugation. If this electricity is generated by fossil fuel chains, there is an associated emission of greenhouse gases (GHGs). However, the GHG emissions, per unit of nuclear electricity produced from the enriched uranium, are much lower than would result from producing the same amount of electricity directly from fossil fuels. Also, there is a small greenhouse gas contribution caused by leakage of flourocarbons (CFC) from enrichment plants. In summary, the main impacts from the uranium enrichment step are the ‘normal’ occupational health effects resulting from ‘conventional’ (non-radiological) industrial accidents occurring in the facilities.

III.4.3.4. Fuel fabrication

Nuclear fuel fabrication processes vary according to the reactor technology. In all cases they involve mainly classic chemical and technical processes. Owing to the low levels of radioactivity present in natural or enriched uranium, radiation doses to workers are quite low. Precautions have to be taken against risks of uranium inhalation. Mixed uranium/plutonium oxide (MOX), utilising plutonium recovered from spent fuel (in the closed cycle), has a higher level of radioactivity and has to be processed in sealed and shielded facilities.

The impacts from fuel fabrication do not make an important contribution to the total nuclear chain impact.

III.4.3.5. Nuclear power plants

During normal operation (severe accidents are discussed in Annex V), liquid and gaseous effluents from nuclear power plants are monitored and controlled in order to minimise the radioactivity released to the environment and, in any case, to maintain it below the levels authorised. Radiation doses to nuclear power plant workers are closely controlled and limited by the applicable regulations. The associated low-dose health impacts to workers and the public are estimated by dose-effect relationships [9]. Owing to the radioprotection rules and regulations in place, these impacts are very limited and in most cases in the range of estimated health impacts from radiation doses received from the natural background and medical applications. Non-radiological occupational effects result mainly from ‘conventional’ industrial accidents.

Cooling systems increase the temperature of the heat receiving water body. Impacts from the release of heated water are localised, owing to rapid dilution in seas or rivers, and have no measurable effects on human health. Care has to be taken, however, to ensure that heat releases do not cause damage to aquatic ecosystems.

During construction and decommissioning of nuclear power plants, local impacts associated with civil works and transportation of heavy components are similar to the impacts arising from classic thermal power plant construction, namely: noise, dust emissions, landscape disruption, interference with population, fauna and flora, and soil alteration. Health impacts to workers arise mainly from accidents during the construction and dismantling activities. During decommissioning, the presence of radioactivity materials poses a small risk of some (very low) public and occupational exposure.

The solid wastes from nuclear power plants are sorted, treated and conditioned according to their respective levels of radioactivity. After appropriate conditioning, low, intermediate and high level radioactive wastes are transported to interim storage and final disposal repositories (see below).

Occupational health effects, radiological and non-radiological, occur during operation of nuclear power plants in routine operation. The main effects are non-radiological health impacts (routine industrial accidents) during construction and decommissioning, although these impacts are rather small per unit of electricity generated. Potential public health effects resulting from low-level emissions of long-lived radioactive isotopes generally are assessed by: (1) calculating the total dose to the world population during a very long time period (more than several centuries); (2) assuming that the health effects follow a linear dose-effect relationship with no zero-risk dose threshold. Using this very conservative approach, the health effects of nuclear power are estimated to be significant, although it must be emphasised that the calculated effects are too low to be measurable in comparison with the natural level of their occurrence (e.g. owing to the natural background radiation).

III.4.3.6. Spent fuel conditioning

Irradiated spent fuel, discharged from the reactor after some three years of energy generation in the nuclear power plant, is stored at the reactor site to allow radioactivity decay and cooling. When the open cycle has been chosen, the cooled spent fuel is conditioned and transported to spent fuel repositories for disposal (see below: radioactive waste disposal).

III.4.3.7. Spent fuel reprocessing

Reprocessing of spent fuel is carried out, in the closed cycle, in order to separate recyclable fissile materials, uranium and plutonium, from the waste products. A typical reprocessing plant includes spent fuel storage pools, workshops for physical and chemical processing, effluent treatment, solid and liquid waste storage and conditioning.

Gaseous emissions and liquid effluents from reprocessing plants are monitored and controlled in order to keep the radioactivity released to the environment below authorised levels. Automation and remote control ensure that worker exposure to radioactivity remains as low as possible. Occupational radiological health effects are estimated by monitoring the doses received by workers, and applying the linear dose-effect relationship. Non-radiological occupational health effects are estimated by analogy to other chemical industries (statistical data based on experience in reprocessing plant operation is not representative, owing to the small number of facilities and the lack of long term operation). Public health effects are estimated on the basis of calculated collective dose to population and linear dose-effect relationships. These effects are not significant in the short and medium term. However, when the estimated effects of long lived radioactive isotopes are calculated for the world population, and over hundreds of thousands of years, the estimated public health impacts become significant. The validity of this assessment approach continues to be debated.

III.4.3.8. Radioactive waste disposal

Radioactive waste generally is classified into three categories: High Level Waste (HLW), Intermediate Level Waste (ILW) and Low Level Waste (LLW). However, the classifications actually adopted vary from country to country according to the rules and regulations in place. In most countries, LLW is disposed of in near surface repositories, while HLW and, in some cases, ILW will be disposed of in deep underground geological sites ensuring their isolation from the biosphere.

Health and environmental impacts from radioactive waste management, storage and disposal arise from the risks of leakage from storage and disposal facilities. As for any other step in the nuclear chain, monitoring and controls ensure that radioactive emissions remain below authorised levels. Social impacts are linked with risk aversion and reluctance of communities to accept the implementation of radioactive waste repositories within their surroundings.

III.4.3.9. Transportation

The various steps of the nuclear chain are carried out at different locations, requiring the transportation of materials between sites. Radioactive materials are packaged for transportation according to their radioactivity level and the mode of transportation. Safety standards and recommendations issued by the International Atomic Energy Agency (IAEA) have been followed by most countries in establishing national rules and regulations for radioactive material transportation.

The estimated impacts from transportation within the nuclear chain arise roughly equally from public radiation exposure (from potential low level radioactive releases along the transit routes) and non-radiological road and railway accidents. Overall, the impacts from transportation are smaller than from any other step in the nuclear energy chain.

III.4.3.9. Summary of impacts from the nuclear energy chain

Although there are variations in the quantities and components of the solid waste streams generated by the different types of reactors, there is enough similarity that representative waste streams can be developed by considering the fuel chain for typical light water reactors (BWRs and PWRs), which account for 85% of the nuclear capacity in operation and 80% of the capacity under construction world-wide. The major components of the open fuel cycle (without reprocessing) for light water reactors are listed in Table III.14, together with the major air and water emissions and descriptions of non-emission waste streams for each fuel cycle component. The magnitude of solid wastes has been estimated for a light water reactor plant operating with 32% thermal efficiency.

The closed fuel cycle (with reprocessing and recycle of recovered materials) results in larger quantities of low and intermediate level wastes than in the case of the open cycle, but reduces the inventory of uranium and plutonium in high level wastes, thereby somewhat simplifying the problems of HLW management and disposal. It also reduces the need for mining of natural uranium, owing to the energy value of the recycled uranium and plutonium. However, the overall magnitude of impacts from the closed fuel cycle is similar to that from the open cycle, and therefore is not shown separately in the table.

III.4.4. Biomass chain

The environmental impacts of biomass crop production are similar to those associated with conventional agriculture. Workers face risks in harvesting and transport of crops grown for energy. Monoculture of biomass crops may create conditions favourable for increase of agricultural pathogens and pests. Pesticides, herbicides and fertilisers used in biomass crop production represent risks to workers, surface water and ground water. Relatively high emissions of organic polycyclic aromatic hydrocarbons (PAH) can be produced by combustion of biomass fuel, but these can be minimised by careful control of the combustion process and by emission abatement systems.

Other issues associated with harvesting, transportation, handling and storage of biomass fuel include: nutrient depletion and soil erosion in forest areas; stream sedimentation; changes in the water yield from forest watersheds; land use competition; emissions from wood-handling systems; leachate from wood storage; and accidents in wood harvesting. Regions that experience intensive harvesting will be particularly susceptible to erosion, sediment transport, flooding, nutrient depletion, and terrestrial and aquatic disruption. Owing to the fact that biomass is little used, at present, for electricity generation, no attempt has been made to present data on the full energy chain for biomass in this annex.

TABLE III.11. FULL ENERGY CHAIN IMPACTS FOR A TYPICAL PULVERISED COAL-FIRED POWER PLANT (QUANTITIES PER GWE-YEAR OF ELECTRICITY PRODUCTION)

Energy chain component	Emissions to air or water	Non-emission wastes
Coal mining: surface	- Drainage water containing dissolved solids, suspended solids and acids	- 10^7 t overburden
Coal mining: underground	- Acid/saline drainage water	- 10^5 t solid wastes
Coal preparation (cleaning)	- Particulates to air and ‘black-water’ releases	- 10^5 t solid wastes
Transportation	- Air emissions from trains, barges and/or trucks	Solid and hazardous wastes associated with the transportation industry
Combustion at power plant	- CO_2, NO_2, SO_2, Hg, waste heat, other metals and organic chemical emissions to air - waste heat and boiler-wash waste emissions to water	- 3 x 10^5 t of bottom and fly ash containing trace metals (arsenic, lead, nickel, etc.) and Gbq quantities of radionuclides such as ^{228}Th, ^{230}Th, ^{232}Th, ^{226}Ra and ^{228}Ra. - Some of the boiler-wash waste may need to be treated as hazardous wastes
Combustion at power plant with flue-gas desulphurisation	Same as above but with substantially lower sulphur emissions	Same as above plus 4 x 10^5 t of $CaSO_4$ and 5 x 10^4 t of $Ca(OH)_2$.
Power plant construction and dismantling		Building rubble, possibility of asbestos contaminated materials, soil restoration wastes

TABLE III.12. FULL ENERGY CHAIN IMPACTS FOR A TYPICAL OIL-FIRED POWER PLANT (QUANTITIES PER GWE-YEAR OF ELECTRICITY PRODUCTION)

Energy chain component	Emissions to air or water	Non-emission wastes
Crude oil extraction -on-shore	- 3 x 10^3 m^3 oil lost by blowouts or spills at wells.	- 10^7 m^3 of brine - drilling fluids - wastes associated with cleaning up blowouts and spilled oil
-off-shore	- 10^7 m^3 of brine. - 7 x 10^3 m^3 oil lost by blowouts or spills at wells	- brine that cannot be released to water - drilling fluids - blowouts and spilled oil
Transport to refinery		- 10^4 m^3 of spilled oil - solid and hazardous wastes associated with the transportation industry
Refining of crude oil to residual oil to power plant	- Releases to air including CO_2, NO_2, SO_2 , and organic chemicals	- 10^5 t oil-contaminated waste solids and sludges. - 10^8 t water wastes containing 600 t grease, 3 t phenol, - 7 t chromium, 3 t lead, and numerous dissolved and suspended organic and inorganic chemicals in lesser amounts.
Transportation of residual oil to power plant		- 600 m^3 of spilled oil. - Solid and hazardous wastes associated with the transportation industry.
Combustion at power plant	- CO_2, NO_x, SO_2 , Hg and other metals, organic chemical emissions to air through flue gas - waste heat and boiler-wash waste emissions to water	Solid/ash wastes are less than for coal, unless flue gas desulphurisation is employed, in which case total mass can be similar
Power plant construction and dismantling		Building rubble, possibility of asbestos contaminated materials, soil restoration wastes

TABLE III.13. FULL ENERGY CHAIN IMPACTS FOR A TYPICAL GAS-FIRED POWER PLANT (QUANTITIES PER GWE-YEAR OF ELECTRICITY PRODUCTION)

Energy chain component	Emissions to air or water	Non-emission wastes
Natural gas extraction	- Methane losses	Brine and well condensate
Raw natural gas processing	Flue gas emissions including CO_2, NO_2, various organic chemicals and particulates	Liquid hazardous wastes
Gas transmission to power plant	Methane losses	
Combustion at power plant	- Flue gas emissions including CO_2, NO_x, various organic chemicals and particulates - waste heat and boiler-wash waste emissions to water	Some of the boiler-wash wastes may need to be treated as hazardous wastes. Amounts are small compared with coal or oil
Power plant construction and dismantling		Building rubble, possibility of asbestos contaminated materials, soil restoration wastes

TABLE III.14. FULL ENERGY CHAIN IMPACTS FOR A TYPICAL LWR NUCLEAR POWER PLANT (QUANTITIES PER GWE-YEAR OF ELECTRICITY PRODUCTION)

Energy chain component	Emissions to air or water	Non-emission wastes
Mining of 0.2% U ore		- 10^6 t overburden
Milling and concentration	Gaseous releases including Gbq amounts of radon and liquid releases including Gbq amounts of U, ^{230}Th and ^{226}Ra	- 85,000 t of solid tailings including quantities of ^{230}Th and ^{226}Ra, and heavy metal contaminants
Conversion from U_3O_8 to UF_6	Liquid wastes containing Gbq amounts of ^{230}Th and ^{226}Ra	- 40 t containing residual U and Th
Isotopic enrichment		- 145 t depleted uranium
Conversion and fuel fabrication	Liquid wastes contaminated with Th and U	- 30 t CaF_2
Power plant operation	Gaseous and liquid releases of radionuclides	- spent fuel - LLW associated with plant operation
Waste management		Depends on choice between reprocessing and once through fuel cycle. For the once through cycle, approximately 20 t HLW, 200 t ILW and 800 t LLW
Plant decommissioning	Gaseous and liquid radioactive releases associated with decontamination and dismantling procedures	LLW and ILW associated with dismantling of the plant. Conventional wastes from plant dismantling

REFERENCES TO ANNEX III

[1] ASSUMPÇÃO, M.G., ABREU, D., M Neto, F.P., et al., Referencial para Orçamentação dos Programas Sócio-Ambientais: (Basis for Budgeting Social and Environmental Programmes), vol. I-IV, Comitê Coordenador das Atividades de Meio Ambiente do Setor Elétrico (COMASE) (Co-ordinating Committee on Environmenal Activities of the Electricity Sector), Ministério de Minas e Energia (MME), Rio de Janeiro (October 1994).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidelines for Comparative Assessment of the Environmental Impacts of Wastes from Electricity Generating Systems, IAEA-TECDOC-787, Vienna (February 1995).

[3] BEIJER INSTITUTE, Environmental Impacts of Coal Mining and Utilization, A Study by the Beijer Institute, the United Nations Environmental Programme, the USSR Academy of Sciences and the National Energy Adminstration (Sweden), Pergamon Press, Oxford and New York (1987).

[4] UNITED NATIONS ENVIRONMENT PROGRAMME, The Environmental Impacts of Production and Use of Energy, Part I: Fossil Fuels, Energy Report Series, Nairobi (September 1979).

[5] UNITED STATES DEPARTMENT OF ENERGY, Energy Technologies and the Environment, Environment Information Handbook, DOE/EH-0077, Washington, D.C. (October 1988).

[6] WORLD ENERGY COUNCIL, Environmental Effects Arising from Electricity Supply and Utilisation and the Resulting Costs to the Utility, Report 1988. World Energy Conference, London, UK (October 1988).

[7] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication No. 26, Pergamon Press, Oxford and New York (1977).

[8] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication No. 60, Pergamon Press, Oxford and New York (1990).

[9] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Ionising Radiation: Sources and Biological Effects, New York (1994).

ANNEX IV

ENVIRONMENTAL COST STUDIES AND THEIR APPLICATION

Different approaches may be used for estimating environmental costs of electricity generation, and the way they are applied may vary from situation to situation. The extent to which environmental costs should be considered as external costs, i.e. not borne directly by electricity producers, depends partly on the environmental protection policy of the country and on the control instruments that are implemented [1]. Under a 'command and control' regime involving emission limits, the costs of residual discharges are not internalised and should appear as adders. On the other hand, where a system of emission trading is in force, the environmental costs already are internalised, at least partly, through the trading costs, and the calculation of additional costs depends on the extent to which the rules that permit emission trading reflect variation in marginal damage from source to source. Adders for pollutants subject to emission taxes should take into account the difference between marginal damage costs and marginal revenues raised by the tax.

Assuming that all impacts from electricity generation chains could be quantified, the overall environmental cost of discharges could, in theory, be calculated by estimating the associated damage costs. However, most studies carried out so far highlight the wide range of uncertainties prevailing in assessing physical impacts as well as in placing values on those impacts. Owing to those uncertainties, and to the lack of reliable data, the costs of emission abatement are sometimes used as proxies for external environmental costs, although this approach generally is opposed by economists [2, 3, 4].

While it is difficult, and perhaps even impossible, to quantify all the impacts from an energy chain, its environmental costs may be calculated with a reasonable degree of accuracy by estimating a few dominant impacts. However, the identification of the dominant impacts is based partly on judgmental assessment, and the main impacts differ according to local conditions such as population density, economic development and characteristics of the sites, e.g. presence of historical monuments, recreational areas or natural parks.

The use of damage costs to estimate environmental adders currently is applied in several countries. For example, in the USA, the Bonneville Power Administration employs adders based on damage costs and the State of Massachusetts has adopted this approach as its ultimate goal. Damage costs can be assessed by two approaches: 'top-down' and 'bottom-up'. The 'top-down' approach, which relies on aggregated data, has been the dominant technique up to now, because it is easier to apply. It gives reasonable estimates for average damage costs, but it has some limitations with respect to application of the results to a specific location. Moreover, the use of aggregated data may conceal gaps in the detailed scientific and economic data. On the other hand, the 'bottom-up' approach requires the use of site specific data, and its results might not be representative of average situations.

IV.1. Top-down approach

Table IV.1 provides a summary of external cost values calculated for various electricity generation chains, as derived from a number of studies in the USA [5]. The two values shown for California, which differ by up to a factor of seven in some cases, were calculated by assuming, respectively, that the power plant is located in a densely populated area (in-state) and in a lightly populated area (out-of-state). The large difference in results, up to a factor of seven in the extreme case, illustrates the danger involved in transferring estimates from place to place.

An analysis of the social cost of energy chains in the United Kingdom has been carried out for the UK Department of Trade and Industry by the Centre for Social and Economic Research on the Global Environment (CSERGE) [6].

Table IV.2 summarises the environmental cost adders resulting from this analysis, which was based to a large extent on USA studies.

TABLE IV.1. EXTERNAL COSTS OF ELECTRICITY GENERATION FOR THE USA (US CENTS/KWH)

Study identification	Type of Energy Chain					
	Existing coal plant without scrubber	Existing coal plant with scrubber	Combustion turbine #2 Oil 0.3% S	Natural gas combined cycle	Atmospheric fluidised bed coal 0.5% S	Gasified coal combined cycle 0.45% S
Pace university	10.3	4.0	2.6	0.77	2.6	2.1
Massachusetts DPU	7.7	5.2	4.0	1.4	3.6	3.0
California EC in-state	30.3	10.9	5.3	0.6	5.9	3.8
California EC out-of-state	3.8	2.2	1.5	0.4	1.4	1.0
New York PSC	2.5	1.3	0.8	0.3	0.7	0.5
Nevada PSC	7.9	5.3	3.9	1.4	3.7	3.0

DPU: Department of Public Utilities
EC: Energy Commission
PSC: Public Service Commission

The authors emphasise the illustrative nature of the figures presented and stress the need to undertake more research to enhance the accuracy of the estimated cost adders. The numbers given in the report are not site specific but are intended to provide a 'broad-brush' indication of the relative scale of environmental costs. It should be pointed out that the report does not provide total environmental costs, owing to the fact that a number of impacts have not been valued. Furthermore, the use of different valuation methodologies to derive costs for the various environmental impacts entails some limitations in using the results from the study.

The major uncertainties identified by the CSERGE report concern the environmental costs associated with global warming and severe accidents. Another important omission may be the lack of valuation of intrusion in the landscape, especially for renewable energy systems that may occupy large areas of land in scenic areas. This might add significantly to the low estimates presented in the report for the external costs of renewable energy sources [7]. Some other issues, such as conservation of wildlife, are excluded from the analysis, since the studies upon which the report is based relied mainly on valuing damage to activities associated with the main economic components of the gross domestic product (GDP).

The report considers a range of values for the impacts of severe accidents in the nuclear energy chain, but omits large accidents in the valuation of external costs for other energy chains. A fair comparison between different technologies should include an analysis of the severe accident risks associated with all generating technologies, e.g. dam collapses, accidents in coal mines and on oil rigs. The wide range of cost estimates reported for nuclear accidents reflects, in particular, the effect of incorporating (or not) a 'social cost' of risk aversion, the value of which is based upon judgmental assessments.

TABLE IV.2. ENVIRONMENTAL COST ADDERS OF ELECTRICITY CHAINS FOR THE UK (P/KWH 1990/91 PRICES)

Environmental externality	Type of Energy Chain								
	Existing Coal	New Coal	Oil	Gas	PWR	Solar	Wind	Hydro	CHP
Health									
- mortality	0.32	0.32	0.29	0.02	0.01	0.07	0.04	0.03	0.15[1]
- morbidity	0.12	0.12	0.12	0.04	0.01	0	0	0	0.06
- disaster	NE[2]	NE[2]	NE[2]	NE[2]	0.02[3] 0.05[4] 0.27[4]	0	NE[2]	NE[2]	NE[2]
Crops	0.10	0.05	0.05	0.02	NE[2]	NE[2]	NE[2]	NE[2]	0.02
Forest[5]	84	0.07	0.98	0.03	NE[2]	NE[2]	NE[2]	NE[2]	0.03
Buildings	3.22	0.28	3.77	0.11	0	0	0	0	0.14
GHGs[6]	0.40	0.34	0.35	0.16	0.01	0	0	0.01	0.17

Notes:

1. It is assumed that combined heat and power production uses new coal plants; therefore, impacts are estimated at half the value for new coal power plants.
2. Not estimated and probably positive.
3. Taking into account risk aversion estimated using the Rocard-Smets function.
4. Taking into account risk aversion estimated using the square function.
5. Upper bound of damage estimation.
6. GHGs = Greenhouse Gases; average of the range of estimated damage costs resulting from a doubling of CO_2 concentration in the atmosphere.

* The authors included the following remarks about the results shown in the table:

- Impacts on biodiversity, noise, visibility, water and land were not estimated.
- For GHGs, a risk premium should be added but has not been quantified.
- More qualitative estimations for other chains, not reported in the table, include:
    - For landfill gas, the environmental externalities will tend to correspond to the values for natural gas.
    - For tidal, a potential biodiversity adder of 0.8 p/kWh may be considered, although there is considerable uncertainty about this value.
    - For energy conservation, there is some evidence to suggest an adder of 0.01 to 0.02 p/kWh for the externalities associated with insulating materials and indoor pollution exposure problems.
    - For geothermal and wave power, it did not prove possible to assess a relevant overall adder profile within the time frame of the study.

With regard to global warming, although there is a consensus among experts and policy makers on the need to recognise the risks of climate change, the authors of the study estimated that present scientific knowledge does not allow reliable estimations of the associated external costs. The probability of severe consequences, such as disease epidemics, large scale famine and flooding, resulting from global climate change are not quantified and, therefore, the impacts of global climate change cannot be estimated nor valued within a reliable range. The authors acknowledge that, under these circumstances, it would be sensible to add some form of risk premium, as an environmental adder for greenhouse gas emissions, if one could be calculated.

IV.2. Bottom-up approach

The alternative 'bottom-up' approach avoids many of the difficulties of transferability, by carrying out site specific assessments for different types of electricity generation chains located in different countries. This method requires that careful consideration be given to the choice and use of pollution dispersion models and dose response functions. In particular, local and regional impacts need to be assessed for a wide range of locations, taking into account a number of factors such as the proximity of protected sensitive areas in the terrestrial or aquatic environment.

The ExternE project carried out by the European Commission (EC), the first phase in co-operation with the USA Department of Energy (USDOE), used the 'bottom-up' approach to assess the external costs of different fuel cycles. An accounting framework for quantifying the environmental impacts and social costs associated with the production of electricity from different fuel cycles was developed and applied to a wide range of fossil, nuclear and renewable energy chains for electricity generation. A summary of the main results from the project, published by EC/DG XII in December 1994 [8], is given in Tables IV.3, IV.4 and IV.5. The main findings from the ExternE project point out issues and difficulties similar to those discussed above for the 'top-down' analysis.

TABLE IV.3. DAMAGE ESTIMATES FOR FOSSIL FUEL CYCLES

Damage category	Estimated value (mECU/kWh)					
	Coal		Lignite	Oil		Gas
	UK	Germany	Germany	GT	CCGT	UK
HEALTH						
Public	4*	13	10	11	10	0.5*
Occupational						
Diseases	0.1	0.3	neg.	neg.	neg.	neg.
Accident	0.8	2.0	0.1	0.5	0.3	0.1
ENVIRONMENT						
Agriculture	0.03	0.04	0.02	0.04	0.03	NQ
Timber	0.04	IQ	0.004	0.013	0.008	-
Ecosystems						
Terrestrial	NQ	NQ	NQ	NQ	NQ	NQ
Marine	NQ	NQ	NQ	0.2	0.2	0.001
Fisheries	IQ	NQ	NQ	NQ	NQ	NQ
Materials	1.3	0.1	0.1	0.2	0.1	0.1
Noise	0.2	NQ	NQ	NQ	NQ	0.03

Notes:

GT	Gas turbine
CCGT	Combined cycle gas turbine
NQ	Not quantified
IQ	Impacts have been quantified but not costs have not been valued
neg.	Negligible
*	Public health impact assessed over the UK population only

TABLE IV.4. DAMAGE ESTIMATES FOR THE NUCLEAR FUEL CYCLE IN FRANCE (MECU/KWH AT 0% DISCOUNT RATE)

Fuel cycle step	Local			Regional			Global		
	S	M	L	S	M	L	S	M	L
Mining	$1x10^{-2}$	$3x10^{-2}$	$3x10^{-4}$	0	$2x10^{-2}$	$2x10^{-4}$	0	$2x10^{-5}$	0
Conversion	$6x10^{-4}$	$3x10^{-4}$	$4x10^{-6}$	0	$3x10^{-7}$	$2x10^{-6}$	0	$2x10^{-7}$	0
Enrichment	$1x10^{-3}$	$1x10^{-6}$	$4x10^{-6}$	0	$1x10^{-7}$	$7x10^{-7}$	0	$7x10^{-8}$	0
Fabrication	$8x10^{-4}$	$1x10^{-3}$	$6x10^{-8}$	0	$2x10^{-6}$	$1x10^{-8}$	0	$1x10^{-9}$	0
Power plant									
Construction	$3x10^{-2}$	$2x10^{-4}$	0	0	0	0	0	0	0
Operation*	$1x10^{-2}$	$5x10^{-2}$	$1x10^{-8}$	0	$3x10^{-3}$	$2x10^{-9}$	0	$3x10^{-2}$	$3x10^{-1}$
Decommissioning	$1x10^{-2}$	$3x10^{-3}$	0	0	0	0	0	0	0
Reprocessing	$3x10^{-3}$	$3x10^{-4}$	$3x10^{-6}$	0	$1x10^{-2}$	$2x10^{-3}$	0	$2x10^{-1}$	2**
LLW	0	$2x10^{-5}$	$2x10^{-6}$	0	0	0	0	$1x10^{-4}$	$5x10^{-3}$
HLW	0	$9x10^{-8}$	$3x10^{-2}$	0	0	0	0	0	0
Transportation	$4x10^{-4}$	$4x10^{-4}$	0	0	0	0	0	0	

Notes:

*	Not including reactor accident damage, estimated at less than 0.1 mECU/kWh based on probabilistic data
**	Resulting from very small doses from ^{14}C emissions that are summed over 100,000 years and assumed to be received by a world population of some 10 billion people
S	Short term
M	Medium term
L	Long term
LLW	Low level radioactive waste management and disposal
HLW	High level radioactive waste management and disposal

TABLE IV.5. DAMAGE ESTIMATES FOR WIND TURBINES AND HYDROPOWER

Damage category	Estimated value (mECU/kWh)			
	Wind turbines		Hydropower	
	Delabole UK	Penrhyddlan UK	Sauda Norway	La Creuse France
Noise	1	0.7	-	-
Visual amenity	NQ	NQ	2*	NQ
Impacts of acid emissions **	0.7	0.7	NQ	NQ
Global warming **	0.2	0.2	NQ	NQ
Public accidents	0.09	0.09	NQ	NQ
Occupational accidents	0.3	0.3	>0.003	NQ
Ecosystem impacts	neg.	neg.	2*	NQ
Direct agricultural impacts	neg.	neg.	0.01	NQ
Direct forestry impacts	0	0	0.0003	-
Impacts on water supply	0	0	0.008	NQ
Recreational impacts	NQ	NQ	2*	NQ

Notes:

NQ	Not quantified
neg.	Negligible
*	Results from a study valuing the ecosystems, cultural sites and recreational and aesthetic impacts
**	Impacts of emissions associated with materials production, manufacturing and construction.

The external costs related to global warming impacts and to severe nuclear accident risk aversion may well be dominant externalities for the relevant fuel cycles. These two issues were considered and analysed in the project. However, owing to large uncertainties in the estimation of their value, the corresponding external costs were not incorporated in the results.

It is especially difficult to place valuations on the estimated damages of global warming damages, in the light of:

- the large uncertainty in physical impact estimates (there is barely a consensus on key indicators such as the Global Warming Potential of different gases);
- the likelihood of significant interactions between impact categories that generally are considered separately (e.g. agriculture and water resources); and
- the uncertainties and methodological issues associated with valuing very long term impacts (e.g. establishing credible world population and life style scenarios up to 2100 and beyond, and applying a relevant discount rate to very long term impacts).

However, the ExternE study states that, while very large uncertainties pervade the estimation of global climate change impacts, these uncertainties do not justify the exclusion of the impacts from the analysis of external costs. The study also concludes that, although uncertain, the damages due to global warming probably are the largest external cost of the coal fuel cycle.

Major issues were raised also by attempting to estimate the external cost of low probability/high consequence nuclear accidents (see Annex IV for a more detailed discussion of this topic). These issues relate to two stages of the estimation. The first is associated with the assessment of the risks (i.e. whether to rely on the limited, statistically non-significant, data available from past experience or on estimates derived with the probabilistic risk assessment method for estimating the risk and consequences of severe nuclear accidents). The second issue is associated with the valuation of the impacts, irrespective of which technique is used to estimate risks (e.g. recognising risk aversion and the fact that the 'willingness to pay' for avoiding low probability risks may not be a linear function of the probability).

Attempts were made to value these factors as part of the ExternE project, and figures were presented and discussed in the detailed reports (based on probabilistic data, the potential impact of the most likely severe accidents was estimated at no greater than 0.1 mECU/kWh). However, the uncertainties were so great that nuclear accidents were excluded from the overall framework of scientific assessment and economic valuation presented in the ExternE summary report.

Although the ExternE project used the same basic methodology and accounting framework to assess the impacts from all fuel cycles, it was recognised that the nature of these impacts vary between fuel cycles and that it was not possible to include the same impacts for all the different technologies, nor to make meaningful direct comparisons between fuel cycles. A wide range of uncertainties are involved in the process of quantifying physical impacts and valuing them for any of the fuel chains considered. In particular, the assessed damages cover a very wide range of space and time scales and, in general, the impacts that result from integration over the largest space and time scales potentially are the largest, but also are the most uncertain. Owing to those uncertainties, total damage values have not been calculated for such impacts.

Public health impact coefficients used in the ExternE study are higher than those estimated in previous work, because they reflect results from a number of recent epidemiological studies on the impacts of particulate emissions, coupled with a regional scale analysis of acid aerosols. Although the estimated large mortality damages are uncertain, they show that assessment of power station environmental impacts need to be more comprehensive than in the past.

It should be noted that the damage estimates of the ExternE study are valid only for the technologies and plants considered which, being located within the European Union, are equipped with abatement devices in order to meet the pollution control regulations in force in Europe. Since most impacts depend linearly on the quantity of emissions, damages from power stations without abatement equipment, that are in operation in a number of developing countries and countries in transition, are likely to be many times larger those presented in the study.

The project is inconclusive on whether the impacts of fossil fuel cycles on ecosystems, including crops and forest, can be neglected. With the present stage of knowledge, it was found that these impacts could not be assessed fully even in physical terms, and much less in terms of monetary damages. A number of potential impacts have not been evaluated, including interactions between different pollutants, possible increases in pest damages and changes in climate. These could have significant effects on the damage valuations. In particular, the calculated costs of crop damage are considered to be under-estimated. Given the level of uncertainty, the precautionary principle suggests the use of critical loads as a constraint for taking the impacts into account for electricity system planning purposes.

The analysis carried out by the ExternE project highlights the sensitivity of damage cost estimates to discount rate. This is a major issue in the economic valuation of long term environmental impacts (e.g. effects of low radiation doses over thousands of year), which has yet to be satisfactorily solved.

The results from the ExternE project show the importance of global scale impacts, which often have not been taken into account in other studies, in comparison to the local and regional scale impacts which usually are analysed well. For the fuel cycles considered in the project, all the estimated costs associated with local pollution impacts were small. This is due partly to the fact that, in Europe, major local impacts usually are mitigated by pollution control measures, and the cost of abatement technologies and mitigation measures is internalised in the direct electricity generation cost. However, the study indicates that residual local impacts need to be taken into consideration, even if their estimated damage cost is rather low in absolute terms, because they are focused on specific geographic locations and on few receptors. This highlights the possible need for more stringent environmental controls than may be justified by economic efficiency alone. For renewable energy chains, local impacts are dominant and require detailed site specific analysis at the planning stage, in order to ensure comprehensive environmental impact assessment and economic evaluation.

While not producing definitive valuations for the environmental impacts of the major energy chains for electricity generation, the results of the ExternE study are very valuable and informative. They demonstrate the importance of long term and global damages for fossil and nuclear chains and point out the need for further research in order to reduce the uncertainties on physical impacts and, moreover, to establish better methodological frameworks for valuing long term effects. Based upon the damages valued by the study, there is no evidence that external costs from any of the fuel cycles considered would be large enough to modify significantly the total costs of electricity generation nor to change drastically the relative economic competitiveness among energy chains.

IV.3. Use of external environmental costs in electricity system planning

One example of the use of external costs in the process of electricity system planning by utilities is given in the USA case study carried out within the framework of the DECADES project [9]. This study examined the policies that had been adopted in three States in the USA, requiring the incorporation of external costs into the resource planning process of electrical utilities. The study concluded that, although the requirement to include externalities in the planning process had forced utilities to change their planning approaches, there had been little impact on the resulting choice of energy sources for electricity generation in any of the States considered. It was found that the externality values prescribed by the regulatory bodies had no effect on increasing the penetration of renewable energy sources nor on the deployment of demand side management options. The study demonstrates that there still is a need for further research in this field. Both the regulatory authorities and the utilities are sensitive to the risks of environmental damage, and there is recognition of a need for innovative and effective techniques for effectively treating externalities in the planning and decision making process.

REFERENCES TO ANNEX IV

[1] FREEMAN, A.M., BURTRAW, D., HARRINGTON, W. AND KRUPNICK, A.J., “Weighting Environmental Externalities: How to do it right”, The Electricity Journal, Vol. 5, No. 7, (Aug./Sept. 1992).

[2] JOSKOW, P.J., Dealing with Environmental Externalities: Let's do it right!, Edison Electric Institute, Washington, D.C. (1992).

[3] WIEL, S., “Why Utilities Should Incorporate Externalities”, in Proc. of 2nd International Conference on External Costs of Electric Power, Wisconsin (September 1992).

[4] MARKANDYA, A., Economic Valuation: Externalities of Fuel Cycles, ExternE: Externalities of Energy, European Commission, vol. 9, EC/DG XII, Luxembourg (1995).

[5] OTTINGER, R.L. AND WARD-WILLIS, N.M., “Incorporating Environmental Externalities through Pollution Taxes”, in Proc. of World Clean Energy Conference (Geneva, Nov. 1991), Circle Mondial du Consensus (CMDC), Zurich (1991).

[6] PEARCE, D.W., BANN, C. AND GEORGIOU, S., The Social Cost of Fuel Cycles, The Centre of Social and Economic Research on the Global Environment (CSERGE), Report to UK Department of Trade and Industry, HMSO, London (September 1992).

[7] FERGUSON, R.A.D. , Environmental Costs of Energy Technologies - Development of a Methodology, Report to the UK Department of Energy, Energy Technology Support Unit, Harwell Oxfordshire (1992).

[8] EUROPEAN COMMISSION DIRECTORATE, ExternE: Externalities of Energy, vols. 1-6, EC/DG XII, Luxembourg (1995).

[9] UNITED STATES DEPARTMENT OF ENERGY, ENERGY INFORMATION ADMINISTRATION, Electricity Generation and Environmental Externalities: Case Studies, DOE/EIA-0598, Washington, D.C. (1995).

ANNEX V

SEVERE ACCIDENTS IN THE ENERGY SECTOR

V.1. Severe accident issues

In general, the term 'severe accidents' is understood to refer to potential or actual accidents that, if they should occur, would represent a significant risk to people, property and the environment. In order to have a reasonably complete picture of the full spectrum of health, environmental and economic effects associated with different energy systems, it is necessary to include consideration of health and environmental consequences that can result from potential severe accidents, as well as the impacts resulting from normal operation.

Consideration has to be given to accidents that might occur at fixed installations for storing and processing hazardous materials, or during the transportation of such materials by road, rail, pipelines, open sea and inland waterways. Examples of hazards that need to be considered include fires, explosions, structural collapses and uncontrolled releases of toxic substances outside the boundaries of the installations.

The energy sector is one of the main contributors to severe industrial accidents. At the same time, major gaps exist in the current state-of-the-art for assessing the risks and potential consequences of severe accident for different energy sources. Data based solely on accidents that have occurred in the past provide only a partial picture of the risks and consequences since:

- Conditions (for example with respect to technology, safety principles and culture, physical and operational environment) that are characteristic of a specific event may be such that the applicability of the consequences to the assessment of similar events under other conditions may be questionable, and possibly should be precluded;
- Actual experience, if available, in most cases reflects only a few examples from a wide spectrum of potential accident scenarios;
- For some energy sources and for some parts of energy chains, the statistical evidence available from actual experience is very poor, owing to the fact that, fortunately, only a few accidents have occurred;
- Impact of expected advancements in technology, including improvements of safety systems, are not taken into account when assessments of probabilities and consequences are based only on evaluations of past events.

Consequently, a balanced evaluation of severe accident risks associated with systems having extensive built-in safety features should be based on the use of predictive approaches employing Probabilistic Safety Assessment (PSA) techniques. Evaluations of past occurrence of accidents are nonetheless useful as: (a) supplement to PSA; (b) source of information to support PSA and to identify possible causes and sequences of accidents; (c) sometimes the only available source of data, owing to the limited number of PSA studies that have been carried out.

A particular problem in the evaluation of severe accidents is the distinction between high frequency/limited consequence events on the one hand and very low frequency/extreme consequence events on the other hand.

V.2. Treatment of severe accidents

V.2.1. Definition of severe accidents

A number of criteria related to the level of consequences have been proposed as a basis for the definition of severe accidents [1]. Typically, an accident is defined as 'severe' if it has the potential to cause any of the following:

- Ten or more deaths or serious injuries;
- Evacuation of more than 200 people;

- A ban on consumption of locally produced food or drinking water;
- The enforced clean-up of more than 25 km^2 of land or water;
- A direct economic loss of more than 10 million dollars.

This definition implies a number of quantitative indicators of interest when evaluating past accidents or when carrying out a predictive assessment of a specific energy system. Generally, the indicators can be divided into three groups, according to the effects on: (a) humans, animals and ecosystems; (b) natural resources; (c) property. There is a consensus on the desirability of estimating these indicators, although different opinions may exist with regard to the specific numerical values that define the border between severe and non-severe accidents. Whether it is feasible in practice to generate numerical values for all indicators of interest, and for a variety of energy systems, is a different matter. Current limitations in this respect will be discussed below.

V.2.2. Scope of severe accident analysis

The following aspects affecting the scope of analysis need to be considered when carrying out a comprehensive comparative analysis of severe accidents:

- The comparison should not be made on the basis of the consequences of severe accidents in isolation from other events that also can cause major health and environmental effects. Also, the associated accident frequencies must be estimated. In practice, this represents the major difficulty and challenge of accident analysis. Generic information on such parameters has a limited applicability and, if used, must be treated with great care.
- The comparison should not be limited to only the electricity production (power plant) step, but should include other steps of the energy chains also (i.e. energy resource exploration, extraction, transportation, processing, storage and waste disposal). For some energy chains, these other steps may represent a larger hazard than the power plant itself.
- Time and space dimensions of accident consequences are important. The following categories have been suggested by the IAEA [1]:

Time:	Short term	(direct impacts - up to 1 yr.)
	Medium term	(within a human lifetime - about 70 years)
	Long term	(inter-generation)
Space:	Local	(most impacted area or population group)
	Regional	(national, continental or international)
	Global	

- The current state of knowledge concerning delayed health effects, as well as for long term environmental impacts, from severe accidents associated with different energy systems is limited. Consequently, the assessment results frequently cover only immediate/acute health effects.
- Not all aspects of severe accident analysis are amenable to quantification. This applies in particular to environmental effects such as: loss of quality and aesthetic values; disturbance of the ecosystem or genetic deterioration; possible irreversibility of damages; and social impacts of psychological nature. In the context of decision making, these aspects may have to be treated qualitatively, rather than quantitatively.

V.2.3. Sources of information on past accidents

Several commercial and non-commercial databases on past natural and man-made accidents constitute a major source of information on past accidents. Table V.1 shows a non-exhaustive list of databases providing information on major accidents [2].

TABLE V.1. DATA BASES ON MAJOR ACCIDENTS

Full name (Organisation)	**Country of origin**	**Code name**	**Time**	**Area covered**	**Scope of the accidents**
Office of Foreign Disaster Assistance Database (OFDA)	USA	OFDA	1900-1995	World	Man-made and natural Ccatastrophes
Resources for the Future (RFF)	USA	RFF	1945-1991	World	Man-made and natural catastrophes
Acute Hazardous Events Database (EPA)	USA	AHE	1900-1995	USA	Chemical accidents
Minerals Management Service Accident Database (access through WOAD)	USA	MMS	1970-1995	USA	Offshore
Major Hazards Incidence Data Service (SRD)	UK	MHIDAS	1900-1995	World	Industry
Casualties and Demolition Database (Lloyd's)	UK	LLOYD'S	1976-1995	World	Offshore
MARCODE (HSE)	UK	MARCODE	1985-1995	UK	Industry
SIGMA (Schweizer Rück)	Switzerland	SIGMA	1969-1995	World	Man-made and natural catastrophes
WOAD Offshore Databank (DNV)	Norway	WOAD	1970-1995	World	Offshore
Failure and Accidents Technical Information System (TNO)	Netherlands	FACTS	1920-1995	World	Industry
SONATA (TEMA/ENI)	Italy	SONATA	--	World	Industry
Accidents Book (UB)	Germany	HSUB	1900-1983	World	Industry
List of Failed Dams (ICOLD)	France	ICOLD	1850-1992	World	Dam accidents
VARO (LRIOH)	Finland	VARO	1978-1987	Finland	Man-made and natural catastrophes
Emergency Preparedness Canada Disaster Database	Canada	EPC	1900-1995	Canada	Man-made and natural catastrophes
Emergency Disaster Events Database (CRED/CUL)	Belgium	EM-DAT	1900-1995	Belgium	Man-made and natural catastrophes
Inventory of Belgian Catastrophes	Belgium	IBC	1889-1995	Belgium	Man-made and natural catastrophes
Major Accident Reporting System (JRC-ISEI)	European Community	MARS	1980-1991	Europe	Industry

Typically, the following types of information are included in accident databases:

- Time and place;
- Type of hazard (natural or man-made);

- Basic characteristics of the natural hazard (specific type, severity, duration etc.) or of the technology (e.g. energy chain step, size/production capacity, specific process, mode of operation, fuel/input material characteristics);
- Description of the accident, possibly including an analysis with respect to cause, propagation and consequences;
- Specific damages (e.g. immediate/delayed fatalities and injuries, evacuations, observed or assessed environmental impacts, economic losses).

With few exceptions (WOAD, MMS), the databases listed in Table V.1 have not been designed for, nor intended for use in, specifically addressing energy-related events, which constitute a subset of accident events with unique characteristics that need to be identified. Allocation of accidents to specific parts of energy chains is not always straight-forward, since it involves assumptions concerning the boundaries for the chains and for the overall energy system analysis. Apart from the differences in the types of accidents included, the databases differ also with respect to time periods covered, geographical scope and degree of detail in the data. Other sources of information on past accidents include:

- General and specialised literature;
- Annual publications (encyclopaedias, almanacs);
- National and international newspapers;
- Reports and lists maintained by consulting and engineering companies;
- Consular services and intelligence agencies;
- National and international emergency services;
- International organisations (Red Cross, United Nations);
- National and international associations and engineering societies.

There exists a great richness of material on accidents, but few attempts have been made to evaluate systematically the available information, owing to the requirements for quite extensive resources and continuous updating. The pioneering work by Fritsche [3] on energy-related accidents was used as a basis for the estimates presented in 1991 at the IAEA Symposium on Electricity, Health and the Environment [4]. Work using much more extensive source material currently is in progress [2, 5], but problems with completeness and reporting accuracy are inherent for this type of activity. For example, a number of databases listed in Table V.1 contain information on a liquefied petroleum gas (LPG) explosion that occurred in Mexico City on 19 November 1984. The number of fatalities reported for this accident ranges between 452 and 550, while the number of persons injured varies between 2500 and 7231. Some reasons for completeness and reporting accuracy problems are [2]:

- Policy decisions in the country of origin;
- Policy decisions by the receivers of information;
- Commercial confidentiality;
- Military confidentiality;
- News value;
- Language barriers;
- Lack of knowledge about the actual consequences (especially indirect ones);
- Human and organisational factors.

V.2.4. Probabilistic safety assessment

Probabilistic safety assessment (PSA) provides a structured and logical approach for identifying credible accident sequences, assessing the corresponding likelihood, and delineating the associated consequences.

PSA techniques were developed mainly within the nuclear industry. In a relatively short time (less than 20 years), PSA has been transformed from a research topic into an established standard tool for safety work. Subject to suitable modifications, and frequently under the name of quantitative risk assessment (QRA), PSA has been adopted within the space, offshore oil and process industries. However, this has been subject to substantial country-to-country variation and to a narrow range of applications. This stems partly from the fundamental differences between the nuclear industry (which essentially deals with a single process) and the other industries (where a multitude of inter-dependent processes may be at work within the same plant). Many facilities within the different energy chains exhibit similarities with the process industry. In a number of countries (particularly the Netherlands, UK and USA), applications of QRA within the process industry are extensive and growing steadily.

One of the important capabilities of PSA lies in the possibility of representing design and site-specific features which may have a decisive impact on the results from evaluations of the potential consequences of severe accidents. The view of the industry, and of a vast majority of the regulators, is that the most important insights provided by PSA are the engineering ones. The use of the results in the '*relative*' sense (e.g. identification and ranking of the dominant accident sequences) is considered to be more robust and mature than the direct use of '*absolute*' results which are of interest in the comparative evaluations. The latter is subject to larger uncertainties and places a greater burden on the completeness of the analysis. The fact that more confidence can be placed in 'relative' insights by no means disqualifies the 'absolute' uses. If used properly and with caution, the 'absolute' PSA results have an indisputable merit as one indicator among others in comparative studies of various energy systems.

V.2.5. Subjective risks

Risk estimates based on experience or on PSA provide a technical measure of the level of risk. However, subjective views on risks play a role also. Experience shows that the influence of subjective risk aversion on behaviour of individuals can be significant. Degree of aversion is in turn dependent on the magnitude of the potential accidents. Risks are integrated by combining the magnitude of the consequences with the associated frequencies. The expert based risk estimates employ the so called 'product formula', in which the frequency of an accident is simply multiplied by the magnitude of its consequences. Some studies account for risk aversion by explicit or implicit allocation of extra weighting to events with very large consequences. Aversion frequently is introduced as a power factor, i.e. the damage magnitude is raised to the power of the aversion factor. By definition, aversion factors are greater than one and in most published studies do not exceed two. With an aversion factor of two, a single event causing 10 deaths is valued the same as 100 events with one death each. If aversion exponents in the high range are selected, then the subjective risks clearly overshadow the objective ones.

Quantification of risk aversion remains a controversial matter. The primitive approaches illustrated by the example above have no empirical justification and are based on ad hoc arguments. An example of more advanced methods is the 'revealed preference analysis' approach developed by Pratt [6] and Arrow [7], whereby the parameters are estimated from market prices on financial or insurance markets. One concern in this context is the applicability of parameters reflecting aversion towards risky investments for application in quantifying the aversion towards accidents. Recently Krupnick et al. [8] proposed, in the context of the EC/US study on external costs of fuel cycles, an approach that is in accordance with economic theory and that aims at estimating the difference between results based on the 'expert expected damage' approach and on the 'risk valuation' approach. Also in this approach, reliable empirical information is lacking, particularly with regard to the appropriate utility function and the degree of risk aversion.

V.2.6. Presentation of results

Presentation of results on risks associated with the different energy systems is a subject of ongoing discussions. For the case of electricity generation, the estimated damages are frequently normalised to the amount of electricity generated. While this form is valid, it is necessary to use alternative and complementary indicators for comparison, such as frequency/consequence diagrams that illustrate the potential for extreme consequence accidents. It is desirable (although feasible in only some cases) to cover the different types of damages associated with the different energy systems. Subjective risks, if quantified, should be presented along with the expert based estimates, in such a way that the numerical difference between the two diverse types of estimates is apparent. In case the results include estimates based on both past experience and on predictive approaches, the origin of the different estimates should be specified clearly.

V.3. Some insights and examples of results

V.3.1. Chain specific nature of potential severe accidents

Based on experience and on risk analysis studies, it may be concluded that the potential for severe accidents is concentrated to specific parts of the different energy chains [4]:

Energy chain	*Types of potential severe accidents*
Coal	Explosions or fires in underground mines; collapse of roof or walls in underground or surface mines; collapse of tailing piles; vehicular accidents during transportation.
Oil	Off-shore rig accidents; fires or explosions resulting from leaks or process plant failures; blowouts of oil wells; transportation accidents resulting in fires and explosions; leakage from oil storage tanks, leading to fires or explosions.
Natural Gas	Same as for oil chain.
Nuclear (LWRs)	Loss of coolant water; reactivity transient and reactor meltdown; accidents during shipment of high level radioactive waste.
Hydropower	Rupture or over-topping of dam.
Geothermal	Well blowouts, resulting in the release of toxic gases.
Biomass	Not identified.
Wind	Failure of large rotating equipment, with broken parts becoming missiles in densely populated areas.
Solar Photovoltaic	Release of toxic materials during photocell manufacture.
Solar Thermal	Release of toxic heat transfer fluids.

V.3.2. Examples of results from current studies

Paul Scherrer Institute (PSI) established recently a database on severe accidents, with emphasis on the energy-related ones. It combines the relevant information provided in such databases as OFDA, RFF, MHIDAS, SIGMA and HSUB (see Table V.1), and a number of additional sources listed earlier. Currently, the PSI database contains information on more than 3300 energy related accidents.

Figure V.1 shows the estimated number of immediate fatalities per unit of energy for five different energy chains, based on worldwide accident records; only accidents with at least five fatalities have been included. The results are compared with the corresponding estimates provided in reference 4. The differences are due primarily to the significantly larger statistical evidence in the PSI database. For example, the fatality rate estimated for the oil chain is based on 295 accidents in the PSI database as compared to 63 accidents in reference 4. In addition, consistency in the allocation of accidents to the various energy chains has been improved.

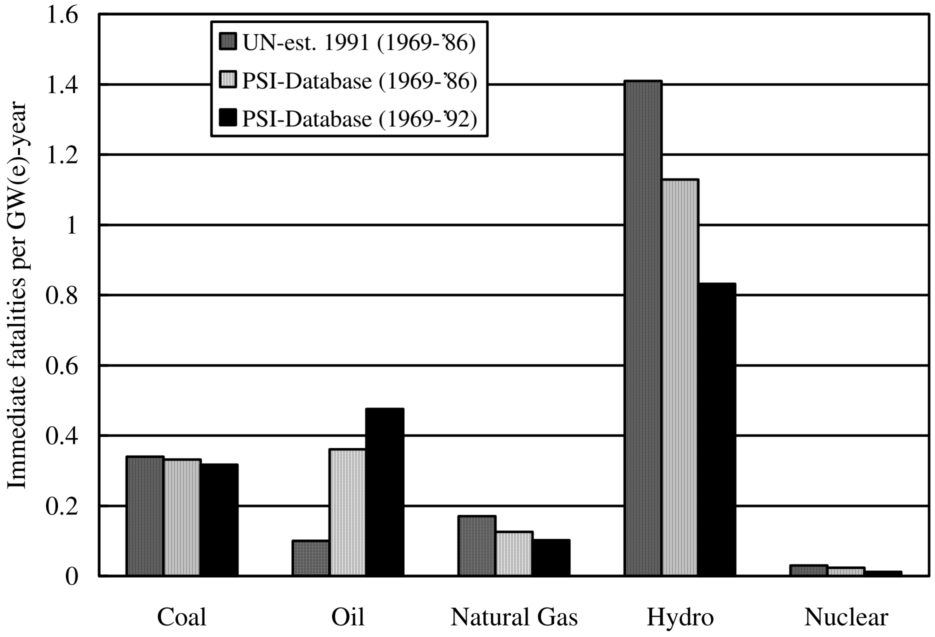
While the immediate fatalities associated with the accident at the Chernobyl nuclear power plant have been included in Figure V.1, the corresponding estimated delayed fatalities are shown in Figure V.2. Normalisation was carried out using the world total nuclear electricity production accumulated up to the end of 1995. The consequences shown in figure V.2 are based primarily on the *assessed doses* received by the emergency workers ('liquidators') and by the public. This applies fully to the estimated number of cancers expected to occur in the future and partly to the results concerning fatalities in the period 1987-1995. For the latter case there is, however, a number of manifested fatal cancer cases among the 'liquidators' and an excessive number (in comparison with spontaneous incidence) of thyroid cancers among children in Ukraine and Belarus. For latent cancer fatalities after 1995, the impact of using dose cut-off criteria is demonstrated.

For energy chains other than nuclear, the potential delayed fatalities due to severe accidents are of a different nature and it is not possible to make estimates with the current state of knowledge. Nonetheless, they are expected to be of much lower importance than the immediate fatalities.

The results shown in Figures V.1 and V.2, when used in the context of current and future electricity supply options at the national level, must be interpreted carefully and preferably supplemented with applicable PSA-based results. As elaborated in Reference 2:

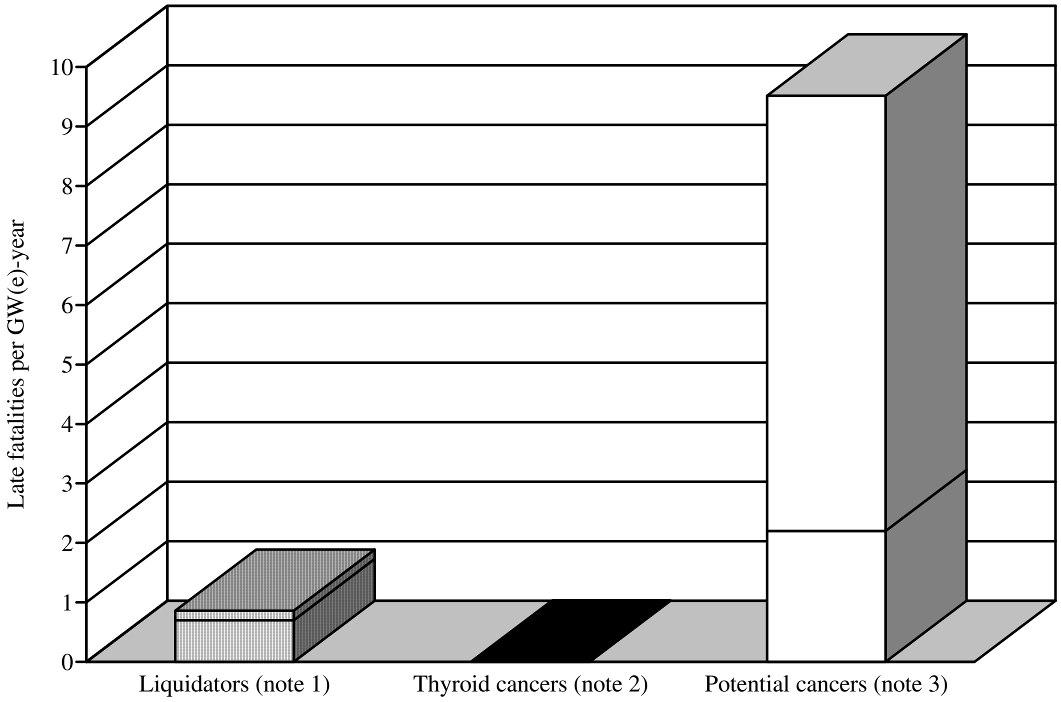
- Only a limited part of the spectrum of possible accidents is reflected by past experience. There are, however, large differences between the various energy chains in terms of the number of accidents that occurred and the average damage per accident; these differences are not explicitly apparent from Figures V.1 and V.2.

The existing data are not homogeneous. This may be due to: technological variability, country-to-country or region-to-region variability, temporal changes (technological, increased hazard awareness, improvements in efficiency of emergency services, changes in safety regulations, changing consumer habits), differences in definition and categorisation of severe accidents, and under-reporting.



Source: PSI database (November 1996)

FIG. V.1. Comparison of energy related severe accident data.



Note 1:	Potential fatal cancers among 'liquidators'. Lower portion applies to the most exposed group; upper portion represents additional potential cancers among the liquidators.
Note 2:	Thyroid cancer fatalities among children (through end of 1995).
Note 3:	Potential cancers in general population. Lower portion applies to the most contaminated areas (IAEA, 1996) [9]; upper portion represents additional potential cancers in the global population, based on total dose commitment (UNSCEAR, 1993) [10].

Source: PSI database (November 1996)

FIG. V.2. Delayed fatalities estimated for the chernobyl accident.

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Many examples could be presented in order to emphasise the limitations of historical data. For example, in the case of nuclear power plants with high safety standards, probabilistic plant-specific estimates of normalised number of latent fatalities are several orders of magnitude smaller than the results obtained for Chernobyl (shown in Figure V.2). This is due to the differences in technology and operational environment. Thus, the USNRC PSA-based study [11] for five US nuclear plants shows that the contributions of severe accidents are in the range of 0.01 - 0.1 fatalities per GW(e)-year. Also for hydro power, it has been demonstrated that the specific conditions need to be examined carefully. Based on evaluation of the historical data, there is a significant difference between the frequency/consequence (f-N) curves for large dams in Asia and Africa on the one hand and those in America and Europe on the other.

As already implied by the above summary of the chain-specific nature of potential severe accidents, different parts of energy chains provide the dominant contributions to the estimated fatality rates. Depending on the specific configuration of a national electricity supply, this may affect prioritisation in the context of comparative evaluations. For example, most of the severe accidents in the coal chain occur in mining; within the oil chain, accidents during transportation and distribution clearly are dominant; in the case of nuclear and hydro (large dams), the severe accident risks are associated mainly with the power plants.

Figures V.3 and V.4 show the normalised frequency-consequence curves for various energy chains [2]. In the context of *immediate* fatalities (Figure V.3), world-wide historical accident data in the period 1969-1992 were used. The results for the Mühleberg nuclear power plant in Switzerland, shown in Figure V.4, originate from the plant-specific PSA [12] and represent *latent* fatalities; the different curves illustrate the outcome of uncertainty propagation. The range of values for predicted latent fatalities from Chernobyl, given in Figure V.4, reflects the impact of using a dose cut-off. The large difference between the PSA-based results obtained for Mühleberg and the experience-based Chernobyl results illustrates once again the limitations in applicability of past accident data to cases that are radically different in terms of technology and operational environment.

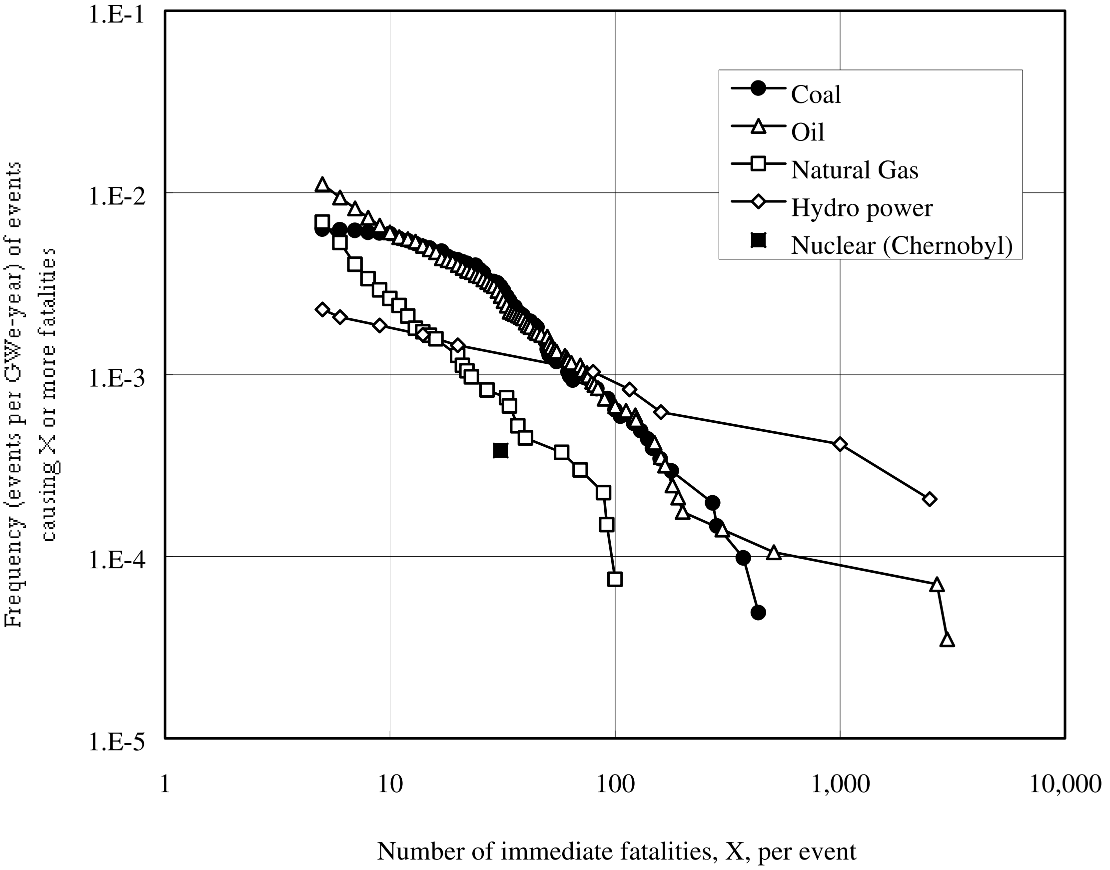

FIG. V.3. Frequency-consequence curves (immediate fatalities) for different energy chains (based on historical accidents worldwide in the period 1969 – 1992).

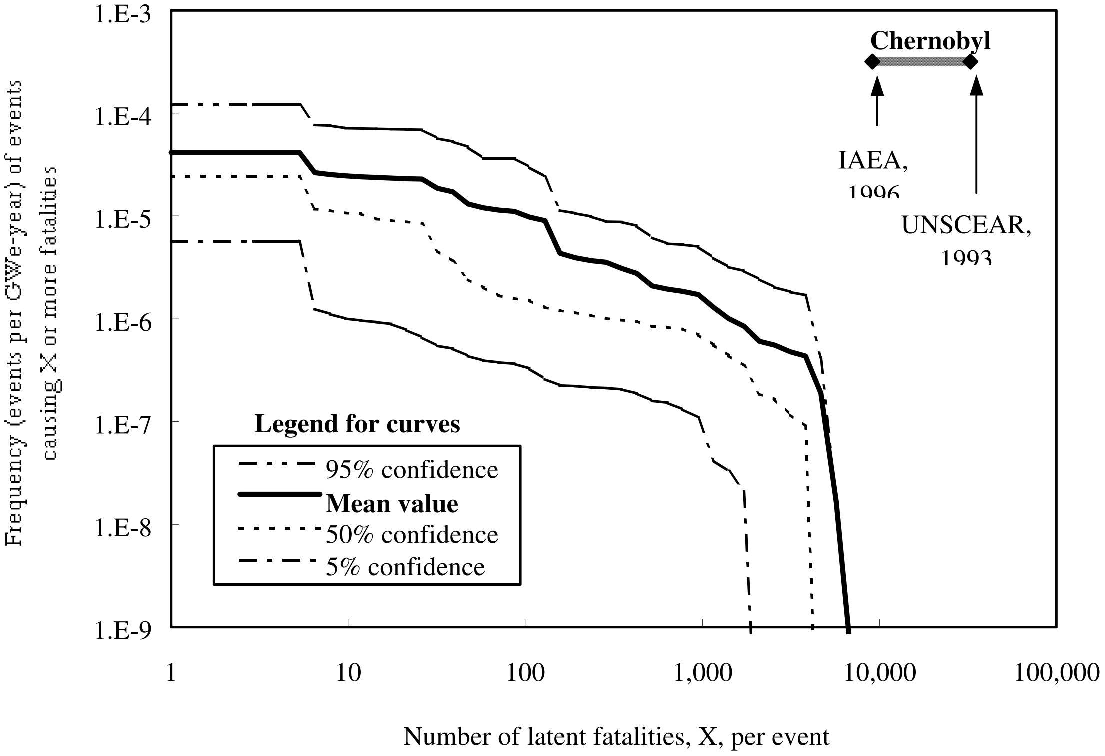

FIG. V.4. Frequency-consequence curves (latent fatalities) for nuclear power [based on PSA for the Mühleberg Plant (Switzerland) and Chernobyl (with and without dose cut-off)].

The full-scope nuclear PSA approach provides results in the form of frequency-consequence (f-N) diagrams and integrated risk estimates for a wide range of consequences. Typically, reported risk estimates include: number of early (acute) fatalities and injuries; number of latent cancer fatalities; total population dose from all pathways; individual risk of death and individual probability of latent cancer fatality; interdicted and condemned land area. For other energy systems, a very limited number of probabilistic studies exists. Due to the scarcity of information, poor statistical evidence and lack of accuracy of historical data, the evaluation of consequences in the context of comparative analysis currently is meaningful for only a few damage categories. In relative terms, the uncertainties are smallest for the estimates of immediate fatalities and are substantially larger for estimates of the number of nonfatal injuries. Relatively reliable evidence exists with respect to major oil spills. On the other hand, the damages caused by oil spills are not necessarily proportional to the amount of oil released, but depend to a very high degree on local conditions and sensitivity of local ecosystems. Economic losses associated with major accidents can be estimated partly on the basis of insurance records. However, there normally is a large discrepancy between the awarded compensation and the ‘real’ loss, including also the indirect damages.

The contribution of severe accidents to the external costs of power production (particularly by nuclear power plants) is a much debated issue. In fact, based on the results of a number of studies carried out between 1988 and 1994, the discrepancies between the results are by far largest when the estimates of the normalised costs of nuclear accidents are considered. The estimated values cover a range of some five orders of magnitude.

As elaborated in [13], the factors and features that have the major influence on the results are: approaches used for the estimation of accident frequency and magnitude of consequences; scope of analysis; nature of risk integration (in particular accounting for risk aversion); and economic parameters used. Extremely high results were obtained in studies that used the Chernobyl plant and accident as being representative for all nuclear power plants, and/or that included consideration of risk aversion. No consensus exists on the appropriate methods and data to be used for quantifying risk aversion, nor on whether risk aversion should even be included in the estimates of external costs. There is, on the other hand, a wide agreement that risk aversion is an indicator for the acceptability of specific energy technologies, particularly nuclear. In the context of external costs of non-nuclear energy chains, little attention has been given to severe accidents, which frequently have been ignored or treated in a very simplistic manner.

V.4. Current issues in comparative assessment of severe accidents

The following short summary of issues should not be regarded as exhaustive, but it can serve as a reminder that, while the topic of severe accidents plays a rather important role in policy making for the power sector, there are a number of questions that remain open [5]:

- *Non-uniform level of knowledge and limited scope of applications of risk analysis.* Few comprehensive PSA/QRA studies have been performed for energy chains other than nuclear, although there is a steadily growing number of applications for offshore, fuel transport, refineries, gas storage, etc. Regrettably, few such studies are published and available to potential users.

- *Difficulties to cover a wide range of consequences in a consistent manner.* There is a discrepancy between the wide range of consequence categories covered by the definition of severe accidents and the current possibilities to quantify their extent and the associated likelihood for different energy technologies. For this reason, comparisons of quantitative indicators usually are limited to very few categories.

- *Treatment of the distribution of impacts in time and space.* Given the increased uncertainty in the long range assessments, there is a need to agree on reasonable analysis boundaries that reflect the priorities of decision makers. This issue applies also in the context of assessing impacts from normal operation.

- *Applicability and transferability of severe accident data.* When analysing a specific facility, any use of generic or plant-specific data (available for a plant other than the one being examined) must take into account technological, operational, cultural and environmental differences. This inevitably involves use of judgement.

- *Treatment of risk aversion and non-quantifiable social detriments associated with extreme accidents.* Further research hopefully will help to improve and balance the currently not very encouraging situation, but is not expected to resolve fully this issue in the near future.

REFERENCES TO ANNEX V

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Comparative Assessment of the Health and Environment Impacts of Various Energy Systems from Severe Accidents, Working Material, Proceedings of a Technical Committee Meeting Organized by the IAEA, 1 - 3 June 1992, Vienna (1992).

[2] HIRSCHBERG S., SPIEKERMAN G. AND DONES R., Severe Accidents in the Energy Sector, PSI Report, Paul Scherrer Institute, Würenlingen and Villigen, (to be published 1998).

[3] FRITZSCHE, A.F., The Health Risks of Energy Production, Risk Analysis, 9(1989)565.

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Electricity and the Environment: Key Issues Papers (Publication from a Senior Expert Symposium, Helsinki, May 1991), STI/PUB/899, Vienna (1991).

[5] HIRSCHBERG, S., “Framework for and Current Issues in Comprehensive Comparative Assessment of Electricity Generating Systems”, in Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making (Proc. Int. Symp., Vienna, 16-19 October 1995), IAEA, Vienna (1996).

[6] PRATT, J.W., Risk Aversion in the Small and in the Large, Econometrica, 32(1964)122.

[7] ARROW, K.J., Essays in the Theory of Risk Bearing, North Holland, Amsterdam, 1974.

[8] KRUPNICK, A.J., MARKANDYA, A. AND NICKELL, E., “The External Costs of Nuclear Power: Ex Ante Damages and Lay Risks”, American Journal of Agricultural Economics, 75(1993)1273.

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Background Papers 1-8, EC/IAEA/WHO International Conference, One Decade after Chernobyl: Summing Up the Consequences of the Accident, 8-12 April 1996, IAEA Proceedings Series, Vienna (1996).

[10] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, 1993 Report to the United Nations General Assembly (with Annexes), United Nations Sales Publication E.94.IX.2, United Nations, New York (1993).

[11] UNITED STATES NUCLEAR REGULATORY COMMISSION, Severe Accidents Risks: An Assessment for Five U.S. Nuclear Power Plants, Final Summary Report, Report NUREG-1150, Washington, D.C. (1990).

[12] CAZZOLI ET AL., A Regulatory Evaluation of the Mühleberg Probabilistic Safety Assessment, Volume II: Level 2 (Limited Distribution), ERI/HSK 93-304, HSK 11/356 (1993).

[13] HIRSCHBERG, S., “External Costs of Electric Power Generation: Are Accidents Adequately Treated?”, Schweizer Ingenieur und Architekt, 20(1995)469.

ANNEX VI

CORPORATE INTEGRATED RESOURCE PLANNING A STRATEGIC PLANNING INPUT TO 1996-1999 BUSINESS PLANNING [1]

SUMMARY

In May 1994 the President asked Corporate Strategic Planning to lead an integrated resource planning exercise to investigate investment directions as an input to the following year's business planning process. Key elements of integrated resource planning were to be applied, such as:

- including a wide range of energy service options;
- integrating the environment with economics, and using full cost accounting to the extent possible;
- including uncertainty by considering key electricity business risks; and
- involving external stakeholders throughout the process.

Based on these elements of IRP and the purpose of the exercise, a cross-business unit team was formed, including representatives from both unions; and the team operated by consensus. An 18 member external Review Group was formed to advise the internal team at key stages throughout the process. The Review Group represented a wide range of customer, consumer, environment and business perspectives. The entire process is known as Hydro's Corporate Integrated Resource Planning (CIRP). As well as investigating investment directions, CIRP was to recommend draft strategic guidelines as an input to 1996-1998 business planning.

CIRP is an experiment with a corporate, strategic-level planning exercise in a Hydro-controlled process. The process used a 'goals and objectives' approach, identifying four objectives drawn from Hydro's mission statement. Seven different portfolios, or combinations of options representing various investment directions, were constructed to meet one or more of the CIRP objectives. A number of assessment criteria were derived from the objectives, against which the portfolios were assessed; criteria such as net present value costs, damage to the environment, health and safety risk, efficiency, community benefits, net income and debt ratio.

The performance of each portfolio was assessed and evaluated using four different methods. One method assumed median conditions (i.e. median load forecast, cost estimates, discount rates, and current provisions of the Power Corporation Act) and used a multi-criteria assessment to assist in the evaluation of the portfolios. Two other methods formed the uncertainty analyses; one using scenario analyses and the other using sensitivity analyses. The scenarios included 'open access', economic cycles and a sustainable energy future. One open access scenario assumed competition in generation to supply the power pool and the other assumed full retail access. The sensitivity analyses included nuclear performance and fuels prices. The fourth assessment used survey data to take a customer perspective in evaluating portfolios.

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[1] *Note:*

This annex is an excerpt from a document of the same title (dated 29 September 1995) that was prepared by the Corporate Strategic Planning Department of the Ontario Hydro Company (Canada). The material contained herein is reproduced with the written permission of Ontario Hydro. Although some reformatting has been done in order to conform to the style used in this Reference Book, the text has not been edited by the IAEA.

Some figures and tables contained in the original document, which are not essential to the understanding of the planning process that was carried out, are not included in this annex. Also, the Appendixes to the original document are not reproduced in this annex. However, they are available to interested parties, upon request, from the Planning and Economic Studies Section of the International Atomic Energy Agency. Citations to any material from the original document, which is not included in this annex, *are given in italics*.

The significant findings from CIRP are:

1. The existing system is highly valued because:

   - a high portion of total energy can be provided at low marginal costs without the need for major capital re-investment in the near term (next 5 to 10 years);
   - there is sufficient flexibility to provide additional capacity and energy, if and when needed, through short lead time options (e.g. two years or less by returning mothballed units);
   - the infrastructure, including existing real estate, provides opportunities to reuse or derive additional benefits from existing sites (e.g. Hearn, Lakeview, Niagara or Matagami redevelopment) and transmission/distribution rights-of-way (e.g. communications with customers).

2. A future system that adopts a distributed generation approach performs just as well as a more traditional, centralized generation approach under median conditions, based on the CIRP team's multi-criteria assessment. Under the scenario analyses, the distributed approach performs better because it allows greater flexibility with lower estimated impacts in responding to changes. For example: distributed resource options are more consistent with the open access scenarios; distributed generation allows more entrants, and ownership need not be only Ontario Hydro - others could develop and finance the generation options allowing reduction in Hydro's current level of fixed costs and a sharing of risks; distributed resources have shorter lead times for most options which improves load tracking and reduces risks of stranding investments.

   As a proxy for distributed generation, CIRP used generation options that are capable of being located in close proximity to the area of customer demand. Natural gas-fired technologies provide the bulk of the new generation resources: combustion turbine units (CTUs in municipalities), combined cycle CTUs (e.g. repowering at Lakeview and in municipalities), cogeneration (e.g. industrial sites) and district energy using CTU/combined cycle (e.g. in high density areas such as Hearn in Toronto).

   Perhaps most importantly, the distributed generation approach also provides a 'platform for the introduction of highly distributed technologies as they become available. Ultimately, a greater reliance on renewable technologies will mean a highly distributed use of photovoltaic or other technology for individual homes or small clusters of residential housing; or high efficiency non-renewable options (e.g. fuel cells) at commercial centres, such as offices, malls, schools and hospitals.

3. Changes in median assumptions (aside from changes in customer demand as identified in the scenarios) that result in the most significant impacts are: i) changes in nuclear performance; and ii) changes in the long term natural gas price projection. Lower nuclear performance (either life time of units or 10% lower average capacity factors) is a current risk and higher natural gas prices are a long term risk (beyond 2005) if and when gas use becomes substantial.

   Lower nuclear performance can advance the need for acid gas NO_x reduction options to about the year 2000 and can advance actions to reduce or offset CO_2 emissions by three years to 2004 and increase annual costs by about 300 M$.

   Higher natural gas prices (by 30% over median) can result in an annual cost impact of about 250 M$ for about 45 TWh of electricity produced from gas-fired cogeneration, combined cycle and district energy options at today's level of efficiency.

   Lower natural gas prices (i.e. no real price increases) would reduce costs by about 250 M$ per year compared to median conditions. Higher nuclear performance (5% improvement in average capacity factors) would reduce annual costs by 120 M$, thereby accelerating debt reduction and would also defer any major investments for NO_x or CO_2 reductions.

The strategic guidelines that arise from the CIRP process and from Hydro's Consolidated Management Committee workshop where draft guidelines were presented underscore the following:

- the unbundling of costs and developing segregated customer/cost/revenue data bases is consistent with a number of futures because it provides flexibility to adjust customer rate options as required by the business environment;
- energy efficiency opportunities should be targeted for their financial benefit to Ontario Hydro or its customers in aggregate;
- electrotechnologies that can increase/retain Hydro's market share (or reduce loss of market share) of electricity supply should be pursued when there is a net benefit to the environment and to Ontario Hydro or its customers;
- hydroelectric reinvestment to maintain and improve the existing system are preferred, but limited by affordability;
- opportunities for high efficiency cogeneration (e.g. district energy) are the mostly likely type of major re-investments to be made at existing fossil generation sites;
- expected levels of energy production (e.g. 75% to 80% capacity factors as a system average) from nuclear units needs to be achieved using existing, or even fewer, resources;
- grid investments should focus on maintaining the existing system, and new opportunities to introduce 'smart' technologies for customer service and system control should be pursued.

The findings from CIRP and the strategic guidelines are useful for longer term strategy making for Ontario Hydro. The existing system is used to the maximum extent possible to reduce Hydro's fixed costs and provide increased financial flexibility. The increased financial flexibility is needed to weather a highly uncertain period of electric industry restructuring. When needed, natural gas-fired technologies (preferably high efficiency) can be relied on and located to reduce ancillary investments in transmission. Such investments reduce risks of stranding investment relative to most alternatives, and even more so if owned by others. Investments in the grid that use 'smart' technologies would be consistent with operating a more distributed generation system. Adopting a distributed approach with existing gas-fired technologies as a start (e.g. 5 MW to 500 MW) is consistent with the potential for an even more highly distributed system in the future - as noted earlier, providing the platform for the introduction of new technologies.

In a retail access future, choices for energy services would be made by consumers or their energy service provider. Service providers would aggregate customers' demands for capacity, energy and related services with suppliers responding to the market, perhaps by private negotiations with the service provider or by public requests for proposals. Depending on the evolution of the market and the actions of the service providers and suppliers, a satisfactory mix of resource options (e.g. efficiency improvements, renewables, non-renewables) may or may not come about. If the mix is not satisfactory, a regulator may stipulate objectives to be met. An integrated resource planning process could be undertaken at the request of, or even by, the regulator to establish the objectives and identify possible means for their achievement.

INTRODUCTION

This report describes the Corporate Integrated Resource Planning Process (CIRP), its outputs and the evaluation of the process by the internal CIRP team and the external Review Group.

In May 1994 the President asked Corporate Strategic Planning to lead an experiment with an integrated resource planning exercise as a means to investigate investment directions and to report by June 1995 so that CIRP would be one input to the following year's business planning process. Ontario Hydro's corporate mission was the starting point for the exercise and the investments to be considered were those closely related to Hydro's main product: electricity. In June 1994 an internal CIRP team was established. Using the 'elements of IRP' *(see Appendix A)* the team developed a terms of reference in August 1994 *(see Appendix B)*, which sets out the process and schedule. From September 1994 to June 1995, the team carried out the process.

The team completed its task by preparing materials and draft strategic guidelines for a Consolidated Management Committee (CMC) meeting that was held June 6, 1995. The purpose of the CMC meeting was to provide the President with advice and feedback on CIRP findings and the draft strategic guidelines, prior to their finalization as an input to the business planning process.

Following the June 6, 1995 CMC meeting, Corporate Strategic Planning revised the guidelines which were then presented to and accepted by the Strategic Management Committee on June 26, 1995. The CIRP strategic guidelines are included in the President's July 19, 1995 memorandum to business leaders that set out the 1996 - 1999 business planning strategic and process guidelines.

Members of the CIRP team are listed in Appendix C. The team included people from most of the business units and the two unions. The team operated by consensus.

CIRP PROCESS

Figure 1 illustrates the overall process that CIRP followed. Each of the components shown in the figure is described below.

MISSION AND ASSUMPTIONS

A number of planning assumptions were set out early in the process to clearly state: a) boundaries or conditions that were taken as given (e.g. Hydro's mission statement); b) boundaries or conditions placed on Hydro (e.g. acid gas emission limits); and c) conditions that Hydro chooses to adopt in this process (e.g. rate increases at or below inflation). *The CIRP assumptions are listed in Appendix D.* The assumptions do not represent environmental indicators or assessment and evaluation criteria. Such criteria were developed separately at appropriate points in the process. For example, the assumptions about air emissions simply define current regulatory limits and Hydro standards. Operating practises may result in emission levels significantly below limits.

The first assumption, which was also a guiding force throughout the process, is Ontario Hydro's corporate mission:

> *To make Ontario Hydro a leader in energy efficiency and sustainable development, and to provide its customers with safe and reliable energy services at competitive prices.*

OBJECTIVES

Early in the design of the CIRP process, a goals and objectives approach was established. As such, the mission was taken as a statement of the corporate goal and CIRP would be directed towards achieving that goal. Further elaboration of the mission led to the development of a set of objectives. Objectives are widely recognized as essential for informed decision making.

Objectives in any decision or planning context should reflect the underlying values of the individuals making the decision as well as the values of stakeholders. By deriving objectives from the mission, CIRP was explicitly designed to reflect the values of the corporation.

The CIRP objectives contributed to many planning activities: they guided the planning process; they indicated the factors that were important in designing portfolios; and they provided the basis for the assessment of the options and the portfolios, for the comparative evaluation of alternative portfolios and for making trade-offs.

Based on feedback from Consolidated Management Committee and later feedback from the external Review Group, four objectives that CIRP investment direction would aim to achieve were developed. The CIRP objectives are:

- provide competitively priced energy services valued by customers;
- improve environmental performance and make more efficient use of resources;
- enhance social and economic benefits in Ontario; and
- enhance the financial, operational and human resource viability of Ontario Hydro.

CIRP EXTERNAL REVIEW GROUP

An external Review Group provided feedback at key stages throughout the process. A number of people who could represent different perspectives were invited to participate *(see Appendix C)*. They were an advisory group and their participation was voluntary. Norms established by the Review Group participants did not require consensus among themselves; i.e. they were free to have differing views. The Review Group met ten times; *Figure 2 summarizes the meeting dates and main topics.* Typically, the meetings were about four hours in length. At the May 31, 1995 meeting of the Review Group, substantive feedback was received through an eight hour meeting focusing on particular planning issues and the draft strategic guidelines.

OPTIONS

A number of demand/supply options were identified and their main characteristics documented. These options were grouped either by fuel or services. The groups included coal, oil, natural gas, nuclear, water, energy efficiency improvements and other services, waste, wind, solar, peat, wood and transmission. The options also included changes to the existing system, such as fuel conversion, environmental control retrofits or reinvestment and additions that could be made to the existing system such as biomass generation or gas-fired combined cycle generation. In total, over 70 options were characterized for their potential inclusion in investment portfolios.

Additional and non-traditional demand/supply options were identified during the portfolio development stage; options such as a smart energy network, firm power sales and pricing options for environmentally preferred generation. The characteristics of these additional options were generally not defined in detail. Nevertheless, impacts of the options were considered in the assessments and evaluations to the extent practical at the time.

External costs estimates (i.e. monetized values) were provided for selected fossil and nuclear options and expressed in a levelized unit energy cost format. The values were based on existing information Hydro had as a result of the work of an earlier task force on sustainable energy development.

PORTFOLIOS

Seven portfolios, which represent different investment directions, were developed and spanned a 20 year period beginning in 1995. The purposes of the portfolios were to represent specific ways that one or more CIRP objectives could be achieved and to provide a basis for assessing and evaluating the impacts of investment directions. The intention was not to choose one portfolio over another, but rather to understand what components of any portfolio performed well or poorly.

Portfolio 1 aimed to provide customers with more choices at competitive prices. It saw the introduction of a Smart Energy Network as a way to start. Costs would be unbundled for developing rate options, which had the net impact of increasing demand. Demand reducing efficiency improvements would be delayed until a few years before system needs arise. Options were to be selected for low rate impacts in an attempt to minimize revenue requirements.

Portfolio 2 used a traditional low long-term cost approach which included full reinvestment in the existing system over time, customer energy efficiency improvements to reduce demand and to meet new demands, combustion turbine units (CTUs) for peak loads, and CANDU 6's for base loads.

Portfolio 3 relied on renewables and efficiency improvements to the greatest extent of all portfolios. Energy efficiency improvements were pursued more so than in Portfolio 2. Some conversion from coal to gas took place to reduce air emissions in southern Ontario. When major reinvestment in existing fossil and nuclear facilities were needed, the facilities were retired and replaced. Selected hydroelectric redevelopments were also pursued. High efficiency natural gas options were used, such as district heating and fuel cells, and a significant quantity of biomass was the renewable option for filling remaining generation needs.

Portfolio 4 relied on much of the existing system, efficiency improvements, and options that could be sited in close proximity to locations of customer demand. Existing sites were reused (instead of retirement and site release) using cleaner technologies than those that were there before. New options were natural gas fired, using district heating, cogeneration, CTUs and combined cycle combustion turbine units (CC). No new transmission was assumed in order to encourage the distribution of resource options. This transmission constraint also resulted in hydroelectric redevelopments achieving energy benefits but foregoing capacity improvements.

Portfolio 5 focused on options that provide employment and economic benefits in Ontario. There was a high reliance on customer energy efficiency, as in Portfolio 3, and nuclear and hydroelectric options, including the less economic hydroelectric redevelopments and new hydroelectric developments.

Portfolio 6 attempted to achieve an improved balance sheet in a short period of time through capital reductions. A 50% reduction in capital expenditures was assumed, which resulted in near immediate closure of two nuclear stations, Bruce A and Pickering A. The portfolio then had to draw on higher cost options to make up energy shortfalls that resulted in poor performance on many criteria and no useful insights on balance sheet improvements.

Portfolio 7 assumed a number of initiatives to increase revenues; foremost were a 400 MW sale and the elimination of revenue reducing energy efficiency programs.

ASSESSMENT CRITERIA

The detailed specification of the objectives offers the major advantage of providing agreed upon and stated criteria that are capable of weighting for use in the evaluation of the various components of CIRP. Clearly and properly specified objectives guide the evaluation by stating the types of data which would be accepted as evidence of the success of the options and portfolios in meeting the objectives and by indicating the methods of measurement to be used in data collection.

The CIRP objectives were further specified by sub-objectives, from which assessment criteria were identified. An example of a sub-objective is: ‘enhance the financial flexibility of Ontario Hydro and ensure investments are affordable’, and the associated criteria are ‘net income’ and ‘debt ratio’. Another example is: ‘enhance the viability of local and Aboriginal communities’ and the associated criteria are ‘changes in regional and local employment’ and ‘community benefits’.

Eighteen different criteria were used to assess portfolio impacts. The sub-objectives and criteria used are listed below.

CIRP SUB-OBJECTIVES AND CRITERIA

SUB-OBJECTIVE	CRITERIA
Minimize long-term costs	net present value cost (NPV)
Maximize customer valued service	customer value (rates, reliability, power options, consulting services, energy efficiency, environment)
Improve environmental performance	greenhouse gas emissions used nuclear fuel land use non-renewable resource consumption
Minimize adverse community impacts	expected change in local population

Minimize adverse cultural impacts	Aboriginal or minority groups affected
Ensure public safety and health	risk to public health
Make more efficient use of resources	customer and OH EEI
Contribute to the provincial economy	GDP and impact on Ontario employment
Enhance the viability of local and Aboriginal communities	changes in local/regional employment
Enhance the financial flexibility of Ontario Hydro and ensure investments are affordable	debt ratio
Enhance the operational flexibility of Ontario Hydro	technological diversity response to NO_x possible regulation constraints response to CO_2 possible regulation constraints
Ensure worker safety and health	risk to worker health
Enhance the planning flexibility of Ontario Hydro	lead time

ASSESSMENTS AND EVALUATIONS

The seven portfolios were assessed and evaluated using four distinct analyses: a) median conditions; b) scenarios; c) sensitivities; and d) customer-based perspectives.

MEDIAN CONDITIONS

For the analysis under median conditions, the CIRP team used Multi-Criteria Assessment (MCA) to evaluate the portfolios and make the trade-offs. It was felt that MCA has been effectively used for IRPs elsewhere and could help the CIRP Team to:

- communicate about trade-offs among sub-objectives;
- help make more consistent and rational evaluations of these trade-offs;
- understand the values and perspectives of different interests; and
- document how decisions were made.

All seven portfolios were assessed against all the criteria assuming median conditions (i.e. median load forecast, cost estimates, discount rates, and current provisions of the Power Corporation Act). To carry this out, each of the assessment results for each criterion had to be reduced to a value on a numeric scale. The following steps were followed:

1. The outcomes of the assessments were expressed in a variety of units, i.e. dollars, impact on debt ratio, environmental damage in hectares for land use. The individual or team assigned to assess each portfolio against criteria also commented on the significance of the assessment results.
2. These assessment outcomes in their various units were converted into assessment scores to allow the team to evaluate the portfolios with a common set of units. The significance of the assessment outcomes was also used when converting measured units into the assessment scores.

3. The importance of criteria was established by CIRP team members using two methods to provide greater consistency for the importance. Results of the two methods were used to arrive at a single assignment of importance.
4. The assessment scores and the importance of criteria were amalgamated for each portfolio to permit the team to compare the portfolios as a whole. These results were used to broadly identify portfolios that performed well overall and portfolios that did not. Familiarity with the portfolio components and the source of impacts allowed the team to compare individual components of the portfolios. These subsequent assessments were carried out for major portfolio components to evaluate the component's contribution to good or poor performance of the portfolio.

The results of the median assessments and evaluations are summarized in Appendix E.

UNCERTAINTY ANALYSES

For the uncertainty analyses, the CIRP team decided to use two methods: scenario analyses and sensitivity analyses. Key factors in this decision included: a) the number of portfolios that needed to be tested; b) the level of detail of the data being used; and c) the ultimate objective of the CIRP process (strategic guidelines for the more specific business planning process).

SCENARIO ASSESSMENTS AND EVALUATIONS

For the scenario analyses, plausible futures were developed around key uncertainties for Ontario Hydro:

1. "open access" - all or part of the electricity industry is open to more customer choice and competition involving several service providers. The timing and extent of open access could affect the Ontario business environment and Hydro's customer base;
2. economic cycles - increases or decreases in economic activity have a direct impact on Ontario's economy and electricity needs;
3. sustainable energy future - "doing more with less", a steady shift in societal values occurs leading to a focus on energy efficiency, greater use of renewable technologies, tougher environmental regulations, and new business opportunities for Ontario Hydro and municipal utilities.

Five scenarios were developed by the CIRP team to address these uncertainties. They were:

1. Open access: 'Full retail access'
2. Open access: 'Competition in generation to supply the existing power pool'
3. Economic: 'Electric intensity higher than expected' (Ontario booms)
4. Economic: 'The economy rolls over again' (Ontario busts)
5. Sustainable energy future: 'Doing more with less'

Scenario descriptions are provided in Appendix F.

One influential set of assumptions associated with the scenarios was the impact those futures have on the demand for electricity to be provided by Hydro. *Figure 3 illustrates the demand assumptions.*

The assumption of loss of market share under full retail access amounted to a 15% reduction in customer demand on Ontario Hydro. This assumption raised a lot of discussion and debate among the CIRP team and the Review Group. Factors that influenced this assumption are the loss of market share that other monopoly services have experienced with the advent of open access (e.g. Bell long distance), further load-displacement self-generation and sale of their surplus generation, possible municipal utility generation and potential use of transmission interties with neighbouring utilities.

While the extent and timing of loss of market share is not predictable, the threat exists and therefore represents a plausible scenario with which to test investment choices.

The portfolios were be assessed under each of the scenarios by responding to the following set of questions:

- How do the portfolios perform in that scenario? Can they work? What works, what does not work?
- Where are the limitations?
- What are the implications of the scenario for the portfolio?
- Can the portfolios respond to the changes described in the scenarios?

During the assessment the team did not find any material difference, in terms of testing investment directions, between the two open access scenarios because directionally they had similar implications with respect to loss of market share. Therefore only the retail open access scenario was used.

Results of the scenario analyses are summarized in Appendix G.

SENSITIVITY ASSESSMENTS AND EVALUATIONS

Sensitivity analyses formed the other part of the uncertainty analyses. The CIRP team identified four variables that were considered to be significant uncertainties and that would have substantive impacts on portfolio performance. The sensitivity analyses addressed the following uncertainties:

- nuclear generation performance, because about 60% of Hydro's annual electricity production is provided by nuclear generation;
- real discount rate level, because it influences capital investment decisions;
- natural gas price level, because it has been subject to price volatility;
- option cost estimates, because they are one of the key bases on which investment decisions will be made.

Demand projections were addressed by the scenario analyses and therefore were not included in the sensitivity analyses.

Nuclear generation performance

The average annual capacity factors of nuclear units and their lifetime are the two variables that significantly affect a) the cost of nuclear generation; b) Hydro's costs and finances; and c) the air emissions that nuclear offsets.

Since 1988 the average annual capacity factor for all Ontario Hydro nuclear generation has ranged from about 65% to about 80%. These values were used as the low/high values for capacity factor. The high/low limits for capacity factor were assumed in all years of the study period but they were assumed not to affect the amount or timing of the options that make up each portfolio. Portfolio #2 was examined under these conditions.

The life of existing pressure tubes in Hydro nuclear generation stations is about 30 years. If these tubes are replaced, the lifetime of the generating unit will be extended 20-25 years. Therefore, the low end of the unit life time parameter was 30 years, or a unit's retubing date, whichever came first. The high end of the parameter was 50 years. The low limit for unit life was applied to all nuclear units in Portfolio #2. Because units were taken out of service sooner than expected, the amount and timing of options in the portfolio were adjusted and combined cycle gas-fired options were used. The high lifetime value was not analyzed because inspection of the portfolio and judgement on the results indicated that little impact would be seen, largely because the impact is at the end of the planning horizon.

Only Portfolio #2 was assessed because nuclear provides a significant role throughout the period considered. The results can also be applied to the nuclear component of other portfolios.

Impacts on present value costs, air emissions and debt ratio were assessed because changes in nuclear performance can significantly change these factors.

Real discount rate

The real discount rate represents Hydro's real cost of capital (i.e. excluding inflation). It is used to calculate the present value cost of options or portfolios. Generally, lower discount rates tend to favour capital-intensive options (i.e. those characterised by large expenditures in the short term and low expenditures in the long term). Higher discount rates tend to favour less capital intensive options (i.e. those with higher expenditures in the longer term).

The median real discount rate was about 8 % . Historically, it has been in the range of 3% to 5% over the last 30 years. The current rate was comparatively high because (i) current forecasts of inflation over the medium term were significantly lower than historical trends, and (ii) over the medium term (i.e. the next 10 years) 100% of Hydro's financing was assumed to be funded internally, which carries a premium cost over debt. A reasonable range was considered to be 4% to 12%.

Present value costs of the portfolios were recalculated using the low (4%) and high (12%) discount rates. Variations in the discount rate made it necessary to re-assess the portfolios only against the present value cost criterion.

Natural gas price level

This assessment used natural gas price as the key variable because price captures the effects of other variables such as fuel availability, consumption rates and seasonal price variations. High and low values for natural gas prices were set based on earlier work by Hydro on fuel price trends. Natural gas prices higher than median by 30% and more were assumed. The lower prices were moderately less than median. Natural gas prices would have the greatest impact on portfolios 3 and 4, the portfolios that have a relatively high dependence on natural gas fired generation in the latter years of the forecast period. Portfolio #1, which has a more modest gas-fired component, was also assessed. The assessment results could be applied to the natural gas components of the other portfolios.

Changes in natural gas prices made it necessary to reassess portfolios #1, #3 and #4 against criteria related to costs (net present value) and finances (debt ratio).

Option cost estimates

The capital cost estimates of new- options (those in addition to the existing system) in the portfolios were increased by 10%. The impact on net present value and debt ratio were assessed.

Results of the sensitivity analyses are summarized in Appendix G and result highlights are included in a latter section of this report under 'Lessons Learned'. Variations in nuclear performance and natural gas prices provided the most substantive impacts. Variations in real discount rates and capital costs did not significantly alter portfolio performance.

CUSTOMER-BASED ASSESSMENTS AND EVALUATIONS

The Customer-Based Evaluation (CBE) was conducted to provide the customers' perspective for the CIRP. The CBE used information from the Customer Value Index (CVI) and Decision Tradeoff studies that provided the key factors about Ontario Hydro customers value.

The CVI data provided standardized scores which represent the relative ranking of customer expectations and are based on statistically valid samples of residential, commercial and industrial customers. The Decision Tradeoff data provided absolute numeric ranking about which service, product, social and institutional attributes customers would value most. The tradeoff data can indicate how much more the customer would be willing to pay for a particular attribute.

The CBE used the factors provided by the CVI and tradeoff studies to assess the seven portfolios developed in the CIRP from the perspective of four customer classes; Residential, Commercial, Industrial and Municipal Electric Utilities (MEU). The studies directly provided the factors for Residential, Commercial and Industrial and the MEU analysis was based on the Industrial factors. The factors were adjusted for MEU values based on the Planning and Performance Index (PPI).

The CBE relied heavily on the assessment work done in support of the CIRP Multi-Criteria Assessment. The CIRP team developed normalized scores to assess the portfolios' performance against each criteria. In the CBE, the customer factors were aligned with the criteria where possible and new normalized scores were developed to assess the portfolio performance against the factors where practical.

Although the weights differ by customer class, the following were the key factors for all customer classes:

- Reliability of Supply
- Reasonable Rates
- Debt Reduction/Cost Control
- Customer Service
- Environmental Orientation.

The CBE applied the normalized criteria scores to the factor weights; The product of this produced numeric values for each factor which can be summed for each portfolio within a customer class. The portfolios were evaluated and scored somewhat like the CIRP team's multi-criteria assessment. The relative performance scoring using the customer-based perspective resulted in an overall scoring of the portfolios quite similar to the team's.

RESULTS BY PORTFOLIO COMPONENTS

Having completed all the assessments and evaluations of the seven portfolios, the CIRP team constructed results for the major components that make up any portfolio. This approach was used because it was not intended from the outset that a preferred portfolio from the seven would be selected. Rather, the CIRP team wanted to understand which components performed well under a variety of conditions and which did not.

The major portfolio components are Rate Options, Customer Demand Reductions, Internal Energy Efficiency Improvements, Demand Increasing Options, Changes to the Existing System, which includes de-mothballing and reinvestment, and Additions to the Existing System. *The results of all the assessments are organized by portfolio components and are provided in Appendix G.*

In addition to the summary of results, the CIRP team drew out a number of specific 'lessons', taken from the individual assessments and evaluations and from the CIRP process as a whole. These lessons were presented to and reviewed by both the Review Group and Hydro's Consolidated Management Committee.

Lessons Learned

A distributed generation approach performed as well as a centralized generation approach for meeting CIRP objectives.

The distributed generation approach (Portfolio #4) is different than Hydro's more 'traditional' centralized generation approach (Portfolio #2). Portfolio #4 aimed to make transmission additions unnecessary by relying on the existing system and distributing generation geographically to meet demand requirements. Generation technologies employed were mainly natural gas-fired: district heating, cogeneration, CCs and CTUs supplementing most of the existing system (Portfolio #4 did not reinvest in Bruce unit 2). Portfolio #2 fully reinvested in the existing system and relied on CANDU 6 and CTU options to meet increases in demand. Both portfolios had comparable customer demand management programs.

In the CIRP Team multi-criteria assessment, both approaches scored highly. The distributed approach meets a number of dominant criteria - net present value costs, customer valued products and services (e.g. rates, reliability), CO_2 emissions, energy efficiency, and debt ratio. It achieves lower debt ratios in the short and long term than does the centralized approach. However, the distributed approach, with its reliance on natural gas-fired options to meet the majority of new generation needs, begins to exceed the CO_2 target in the long term (2012) whereas the centralized approach does not.

In the scenario assessments and evaluations, Portfolio #4 was judged to offer more financial flexibility and planning flexibility than other portfolios.

The sensitivity assessment and evaluation of natural gas price increases showed Portfolio #4 to still perform well on cost and debt ratio criteria. This is in part because the largest impacts take place toward the end of the planning period and the impact on net income, and eventually debt ratio, has not had time to accumulate as it might. However, the financial and planning flexibility of Portfolio #4 suggests that actions to respond to higher gas prices could be taken while weathering higher gas price impacts for a period of time.

NO_x reduction investments are not a significant short-term business planning issue.

The timing of the need for actions to control NO_x is a function of how much planning flexibility is to be retained. All of the analyses assumed a 9 TWh fossil generation margin was to be maintained. Under these conditions, around the year 2000, Hydro will have sufficient capacity but could be constrained from using it to its potential because of the NO_x emission commitment, unless NO_x controls are installed or equivalent measures taken. Hence, energy production could be constrained. The CIRP team presented the potential energy constraint situation to CMC at the June 6 meeting. CMC discussion did not support maintaining that level of flexibility, which removes the energy constraint being identified by the CIRP team.

Reductions in nuclear performance have a significant impact on: the time it will take to reach CO_2 emission targets; the rate of decrease of the debt ratio; and the amount and timing of NO_x emission control measures.

Lower nuclear performance was assessed by assuming 10% lower average annual capacity factors (about 65% overall) and 30 year unit life times (or major reinvestment dates, whichever came first).

The CO_2 target would be exceeded around 2004 under median load forecast with either lower capacity factors or shorter life times.

The rate of decrease in the debt ratio is affected most, in the short term, by 10% lower nuclear capacity factors. By 2000, the debt ratio would be about 0.06 higher (or 8%) than median; by 2005 about 0.15 higher (or 30%).

For each 3% to 4% reduction in nuclear performance that is replaced by conventional coal-fired generation, a pair of NO_x reducing SCRs (selective catalytic reduction equipment) or an equivalent offset would be needed to leave NO_x emission levels unchanged. With median load forecast and 10% lower nuclear capacity factors, the equivalent of three pairs of SCRs would be needed in 2000 to 2003, while maintaining a 9 TWh fossil margin (i.e. it would take 9 TWh more fossil production than expected to reach the NO_x commitment). A 10% reduction in nuclear unit capacity factors is roughly equivalent to drawing on the full 9 TWh acid gas margin. If the 9 TWh margin is not to be maintained, then no SCRs are needed; but NO_x emissions would be at the level of Hydro's NO_x emission commitment, with no margin for further reduction in planned nuclear (or hydroelectric) energy production.

The value to the system of improving (or the cost of declining) nuclear capacity factors by 1% is currently about 20 M$/a, and rising to about 35 M$/a in the long run.

Fuel cost uncertainty is not significant before 2005 and does not have a significant impact on the relative performance scores of the portfolios.

The impact of higher natural-gas prices is cost related. Prices 30% higher than median result in a cost impact of about 250 M$/a for a portfolio that uses a significant amount of gas - that is about 35 to 45 gas-fired TWh/a. This impact occurs after the year 2005, as little additional use of natural gas occurs before that time. Consequently, debt ratio impacts are not large; and the impact of higher gas prices did not have a significant impact on the relative performance scores of the portfolios.

The cost impacts of lower nuclear performance (as assessed for Portfolio #2) and higher natural gas prices in a distributed generation approach (as assessed for Portfolio #4) are comparable in size, but different in time.

Ten percent lower nuclear capacity factors results in a 300 M$/a negative cost impact in the short term, relative to median condition, and rises to about 400 M$/a in the long term. As described above, the cost impact of higher gas prices is about 250 M$/a in the long term.

The lesson here is that the cost impact of future risks in natural gas prices, for a portfolio that makes substantial use of natural gas, is no different than the current risk of lower nuclear performance.

The Review Group pointed out that the gas price and nuclear performance risks could be additive, and even more if lost nuclear production is made up by natural gas.

Ontario Hydro does not have the ability to assess the human resource impacts of longer term plans.

The CIRP team originally had sub-objectives and criteria to assess the impacts that the portfolios would have on Ontario Hydro staff, consistent with the fourth CIRP objective. However, the team was unable to have the human resource assessments done. Internal resources were not available; and by the time that this was understood, there was insufficient time to consider external resources. As a result, there were no human resource impacts available to be part of the assessment and evaluation process.

Demand management programs with the objectives of building and reducing load undertaken at the same time lead to higher costs (long term present value costs) and poorer financial performance (higher debt ratio).

Emphasizing load building (during capacity surplus) or demand reductions (post-capacity surplus) is more beneficial than equal amounts of load building and demand reductions at any time. This finding was based on the performance of Portfolios #1 and #2. Portfolio #1 places equal emphasis on load building and demand reductions. While the net impact on load is neutral, relative to Portfolio #2 (which focuses on demand reductions), the debt ratio remains higher in the near term (by about 0.07) and is substantially higher in the long run (about 0.27).

Energy efficiency improvements were determined to have more beneficial cost and environmental impacts than supply options. This is demonstrated by comparing Portfolio #7 with Portfolios #l, #2, #4, or #5. For example, in the long term, Portfolio #7, which has no customer demand reducing programs, has a debt ratio that is 0.2 higher than Portfolio #2.

These findings led the team to state: demand management programs with the objectives of building and reducing load should not be undertaken at the same time.

However, a number of Review Group members commented that they did not see any problem with promoting energy efficiency and new uses for electricity use at the same time, provided there was fairness and equity in allocating costs. They saw the CIRP team being unnecessarily concerned, and the CMC discussion of June 6 concurred with that view.

Existing real estate provides significant competitive advantages.

Before there is any change in the control or ownership of existing sites and rights-of-way, the strategic value of the assets in question must be evaluated, including assets surplus to current needs. Existing sites and rights-of-way can provide significant competitive advantages. Rights-of-way, for example, would be the backbone of the Smart Energy Network and are a direct link between Hydro and current or future customers, which is vital to maintain or increase market share.

Distributed generation is typically thought of as small generating units (e.g. in the 10 to 100 MW range) that can be sited close to customer demand locations. However, as applied in

Portfolio #4, large generation (e.g. about 500 MW) located in urban areas is consistent with distributed generation at existing sites with transmission infrastructure (e.g. Hearn and Lakeview).

If the capacity surplus lasts for a long time, then several existing units would likely not ever be returned to service in their current operating mode. Efficiency gains in the transmission system may economize on existing real estate needs. Ways to reuse existing sites and rights-of-way to match local, system and corporate needs could be identified.

Furthermore, there is uncertainty in obtaining new sites and rights-of-way, which increases the value of current sites and rights-of-way.

The CO_2 target (1990 levels beyond 2000) becomes a significant driver for choosing options in the long term under median levels of customer demand.

Generally, from about the year 2007 and onwards adhering to the CO_2 commitment under median conditions strongly influences investment choices. After the impacts of energy efficiency are taken into account, in Ontario, nuclear is the only base load option currently capable of producing energy in the 10s of TWhs that could be added to the existing system without significantly contributing to CO_2 emissions. Portfolios #1, #2, #5, #6 and #7 all ended up with nuclear being added at the back end, and in substantial amounts in portfolios with load building options and without customer energy efficiency improvements. Portfolio #3 relied on biomass rather than nuclear as an option to avoid CO2 emissions. However, the quantity of biomass, 6000 MW, was found to be unacceptable mostly because of land impacts and new transmission requirements. Portfolio #4 meets CO_2 commitments until Pickering A needs to be replaced in 2012. Conversions from coal to gas may help, but were not examined. Other options, such as renewable energy technologies (RETs), need to be pursued to find additional options to manage greenhouse gas emissions.

A number of Review Group participants suggested CO_2 is a social policy matter for government to deal with and lead, even if CO_2 is the most significant global threat to the environment. Some suggest that Ontario Hydro should not jeopardize its viability by investments to meet a CO_2 commitment.

The preferred new fossil generation is combined cycle fuelled by natural gas, especially if it is linked to a steam user.

A couple of drivers push new fossil generation in the direction of district energy developments or combined cycle generation, using natural gas.

Current and forecast natural gas prices combined with existing and well established technology make such developments affordable to a number of investors. High efficiency applications mitigate fuel price risks. With the high efficiency use of natural gas fuel, environmental impacts of operating emissions are low compared to conventional fossil facilities.

Under nearly all the scenarios - open access, economic cycles, particularly ‘boom’, and the sustainable energy future if the option is configured for high efficiency district heating or cogeneration - preferences for new fossil generation point to combined cycle natural gas fired technologies. The option is valued for its planning flexibility and improved environmental performance over coal.

A number of review group members acknowledged the flexibility gas technologies provide, but regret the thought that such a clean resource would be used for electricity generation. Some members felt that because Hydro faced so much uncertainty in the near term postponing investment is forced upon Hydro and a reliance on natural gas technologies is a consequence.

Ontario Hydro does not have a process to determine the relationship between reductions in investments and short to medium term performance of electricity generators.

Portfolio #6 attempted to achieve accelerated debt reduction. The CIRP team was not able to obtain the information needed to properly construct this portfolio (e.g. life-cycle unit and station plans). All that was shown is that aggressive debt reduction (50% less capital, as assumed in Portfolio #6), is not prudent and cannot be made ‘across the board’. If reductions are made, they need to be targeted. CIRP was not able to examine reduced investment/performance relationships.

Many short-term decision guidelines are common over a wide range of possible futures.

Many of the strategic guidelines (next section) are applicable over a range of futures. This likely arises from not having major near term investment decisions; over the next few years Hydro's planned capital investments is an accumulation of many smaller capital projects. Furthermore, a number of the guidelines are consistent with actions Hydro is currently undertaking. Therefore, a number of the guidelines confirm current directions in some areas or reinforce the need to pursue certain directions expeditiously (e.g. guidelines on rate options).

The existing system is highly valued.

The existing system is highly valued for a number of reasons: a high portion of total energy can be provided at low marginal costs without the need for major capital re-investment in the near term (next 5 to 10 years); there is sufficient flexibility to provide additional capacity and energy, if and when needed, through short lead time options (e.g. two years or less by returning mothballed units); and the infrastructure, including existing real estate, provides opportunities to reuse or derive additional benefits from existing sites (e.g. Hearn, Lakeview, Niagara or Matagami redevelopments) and transmission/distribution rights-of-way (e.g. communications with customers).

Smart Energy Network investments are robust under different futures.

One of the few investment directions that performs well with all the futures considered was the smart energy network (SEN). The reason for its good performance is that SEN contributes directly to increasing the products that can be offered to customers and improvements in the operation of the existing system, both of which can increase the value of services to customers. This indicates that investments consistent with a SEN should be beneficial under nearly any future.

DRAFT STRATEGIC GUIDELINES

Business environment

Across most of North America, there are pressures to remove electricity monopolies, especially in electricity generation, and allow customers to access different suppliers in order to gain price advantages. Some customers already have alternative ways to meet their needs at a cost less than Hydro's price. As a result, there is significant uncertainty surrounding Hydro's ability to maintain and create sufficient revenues to recover fixed costs through rates.

Under the median conditions CIRP assumed in its baseline assessments (median conditions of customer demand, median performance of existing generating units and the transmission system, median costs and discount rates, and continuing market share), Hydro would have a healthy future.

However, median conditions seldom persist consistently. The unexpected usually happens; and more often than not, there are negative financial impacts. For example, real electricity prices, net income, customer demand levels, fuel prices and generating unit performances in the early 1990s were far off projections made in the 1980s.

Moreover, in a future where there may be unrestricted competition for energy services, it will not be good enough to have low incremental or marginal costs, if competitors can beat the average prices Hydro has to charge to recover the fixed costs of investments.

Currently Hydro is not able to provide the capital the business units believe is necessary to maintain the full capability of existing assets at adequate levels of reliability for the long term. This suggests that the existing system is not financially sustainable (at full capability and high levels of reliability), unless customer demand, or prices, or both, increase. Alternative approaches to investments and their associated risks need to be considered.

In 1994, around the time that CIRP was starting, Ontario Hydro set out draft strategic orientations *(see appendix of the CIRP terms of reference, Appendix B)*, which, among other things, spoke of Hydro becoming a more commercial and competitive organization. Hydro also set out electricity price commitments for customers and made improving financial flexibility a target.

Improving financial flexibility is one of several CIRP objectives. Generally, CIRP team members weighted financial flexibility higher than most other objectives when broadly evaluating the portfolios under median conditions. However, it is evident from the results of the CIRP scenario analyses, that the impact of lower levels of customer demand raised the importance of financial flexibility for some CIRP team members. This is reflected in the scenario analyses by the choices made to reduce investments to mitigate lost revenues and a deteriorating debt ratio. (Hydro's debt ratio currently stands at about 0.9 and, directionally, it must decrease if financial flexibility is to be achieved.)

Strategic Guidelines

Using the assessment and evaluation results, the CIRP team drafted strategic guidelines for business planning purposes. In doing so, the team was strongly influenced by two views of the future that represented substantively different levels of customer demand. One view was an early introduction of open access in Ontario with a consequent loss in market share and hence customer demand. The other view was continuation of median conditions but with customer demand being anywhere from remaining stagnant at current levels to following the median load forecast projection.

Because of the two views, two sets of guidelines were drafted in preparation for the Consolidated Management Committee meeting on June 6, 1995. A number of the draft guidelines were believed to be robust or flexible enough to be suitable for a number of futures. For example, all of the guidelines under rate options seemed appropriate no matter what the future - at least directionally. Depending on the future there would be differences of necessity and therefore differences in the timing and degree of implementation; but directionally, the guidelines fit a number of futures. Therefore, these were included in both sets of guidelines. In several areas the draft guidelines were slightly different, depending on the view of the future while in other areas, nuclear and fossil in particular, there were significant differences between the two sets of guidelines.

Based on the June 6, 1995 CMC review of the draft strategic guidelines, Corporate Strategic Planning with some further discussion with Market Planning and Corporate Finance revised the guidelines and reduced them to a single set. The guidelines were then included in the President's strategic and process guidelines for 1996 to 1999 business planning, which was issued July 19, 1995. The CIRP strategic guidelines are:

STRATEGIC GUIDELINES FOR BUSINESS PLANNING DRAWN FROM THE CIRP PROCESS, INCLUDING CMC COMMENTARY

PRICING AND SALES OPTIONS

- Develop and implement pricing options to sell surplus capacity and energy. The pricing options should include the flexibility to reflect the changing value of capacity and energy in market prices as the capacity/energy surplus disappears.
- Aggressively pursue export sales contracts.
- Unbundle costs to facilitate the development of packages of service options that customers can choose to purchase.

CUSTOMER ENERGY EFFICIENCY IMPROVEMENTS

- Offer energy efficiency services that have a clear financial benefit for Ontario Hydro or for its customers in aggregate. The energy efficiency services that qualify will meet one or more of the following conditions: the market will pay for the services; customers are retained or gained because of the services; local integrated resource planning processes justify the benefits for the services.

INTERNAL ENERGY EFFICIENCY IMPROVEMENTS

- Quantify internal energy efficiency opportunities and make investment choices based on system marginal costs.

ELECTROTECHNOLOGIES

- Promote and market electrotechnologies which result in a net benefit to the environment, to Ontario Hydro and to its customers in order to increase sales or retain customers.

NON-UTILITY GENERATORS (NUGS)

- Re-negotiate purchase NUG contracts to reduce the impact of the financial premium on ratepayers, where it is economically advantageous and legally feasible.

HYDROELECTRIC

- Re-invest in hydroelectric facilities to maintain reliability and production capability. This is a priority area for Ontario Hydro to ensure a continuation of energy production while maintaining costs substantially below market prices.
- Pursue upgrades and improvements of existing hydroelectric facilities, subject to facility condition, integration opportunity, and capital availability. Hydroelectric upgrades should focus on energy benefits rather than capacity benefits in the short term.
- Planning for the Sir Adam Beck 3 and Matagami redevelopments should continue, and should identify how to derive energy benefits first, while allowing the flexibility to obtain capacity benefits at a later time. A commitment to either of these redevelopments should coincide with establishing energy, capacity or other system needs.

NUCLEAR

- Within the existing capital envelope, invest to achieve nuclear energy production consistent with 75% to 80% capacity factors as a system average of in-service units.
- Operate Bruce unit 2 to its rehabilitation need date (September 1995) and then layup the unit. Do not plan to reinvest in Bruce unit 2.
- Operate Bruce unit 1 to its rehabilitation need date (about 2000). The costs of continuing to plan for the rehabilitation of Bruce unit 1 and other nuclear units should be identified separately, so that the costs of this flexibility measure can be assessed.

FOSSIL

- Be prepared to deliver about 15 TWh of fossil generation annually in the short term and maintain the capability to deliver up to about 25 TWh per year from existing facilities, while not requiring major capital re-investment (e.g. emission control SCRs, station rehabilitation).
- Develop acid gas and greenhouse gas management plans to provide the flexibility needed to meet a range of energy forecasts beyond 25 TWh while adhering to regulatory and corporate environmental commitments.
- Develop the business case(s) for the development of cogeneration at one or more existing sites for the production and sale of energy (e.g. district energy), because significant re-investment at existing fossil sites will depend on the feasibility of cogeneration.

GRID

- Maintain, rehabilitate and refurbish the capability and reliability of the existing transmission system to maximize its utilization, while not requiring major capital re-investments. Focus investments on the smaller transmission improvements, where necessary, that provide increased capability with short payback periods.
- Immediately develop a comprehensive plan for ‘smart grid’ investments, consistent with: benefiting Ontario Hydro; or improving customer choice, service and benefits; or supporting the development of a more distributed generation system.

- Develop legal and business strategies to facilitate partnerships in electricity generation and other energy services to reduce Hydro's financial and other risks.
- Because the existing system is highly valued for its low marginal cost energy production, its flexibility to respond to increased demand and the opportunities afforded by the infrastructure and real estate, ensure that benefits from the existing system are being maximized and contributing to debt reduction.
- Because distributed generation performs well compared to centralized generation and offers more flexible responses to uncertainty, ensure that Hydro is ready to exploit distributed generation and energy service opportunities when the market requires them.

These guidelines were included in the President's July 19, 1995 memorandum to business leaders that set out the 1996 - 1999 business planning strategic and process guidelines.

ANNEX VII

COMMERCIAL LIGHTING REBATE PROGRAM

Cincinnati gas and electric company [1]

Description. The commercial lighting rebate program is designed to provide incentives for installing a high-efficiency lighting technology. The program is not limited to commercial office buildings; any commercial building or industrial office space with inefficient lighting is eligible. Inefficient lighting is defined as standard lighting that averages 3 W per square foot or more, which is the standard level taken from Illuminating Engineering Society (IES) sources for general office space. Although there are a number of efficient lighting technologies available, each with varying degrees of efficiency, this program offers participants a rebate if they use a T8 technology. The T8 technology lies on the upper end of available efficiencies. Future evaluation, research and analysis will address the feasibility and cost-effectiveness of efficient lighting technologies other than the T8 technology.

In general, the Company will provide a rebate, pre- and post-installation inspections, and educational support for the customer. The customer is responsible for the cost of the equipment and installation, as well as any necessary financing.

Study Period. The study period is 20 years. Program participation is expected to plateau by the year 2001, at which time program activity is terminated (refer to Participation and Diffusion sections). Load benefits are realized for 15 years beyond the time that a participant installs the technology.

Target Market. The market for this program is commercial and industrial customers. The industrial sector has only a portion (assumed to be 30%) of its industrial space utilized as office space, where the T8 technology is typically applied. Therefore, the market potential within the industrial sector is assumed to be somewhat smaller than that of the commercial market. For this program, only the retrofit or replacement market is addressed. The new construction market is not considered since it is assumed that more efficient technologies will be adopted naturally in the building design. Moreover, the Company's High-Efficiency Lighting Technical Assistance Program for lighting professionals is targeted to this new construction market.

To be eligible, the potential participant will be the owner of the premises or a building manager on the premise. Since owners and landlords are assumed to be interested in making their property more economically attractive to their tenants, as well as themselves, lessees (renters) are also assumed to be eligible in the program. Long-run competition is assumed to force the savings into the hands of customers.

Billing data indicate that there are 24,680 commercial and industrial customers (15 kW or larger) eligible for the program. It is assumed that the majority of the smallest commercial customers (less than 15 kW) use primarily incandescent lighting.

The composition of the eligible population (all commercial and industrial customers) is diverse; however, it is assumed that the lighting requirements for this group are not diverse. A retrofit application for a large office complex is assumed to differ from a small grocery only in terms of relative size (square footage).

Since the eligible market consists of customers with standard lighting efficiency levels, customers with semi-efficient lighting fixtures are excluded from the market. This is estimated to be

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[1] Note:

This annex is reproduced from the Cincinnati Gas & Electric Company's "1992 ELECTRIC LONG-TERM FORECAST REPORT" for illustration purposes, with the permission of Cincinnati Gas & Electric Company. Although some reformatting has been done in order to conform to the style used in this Reference Book, the text has not been edited by the IAEA.

Some figures contained in the original document, which are not essential to the understanding of the programme described, are not included in this annex. Citations to any material from the original document, which is not included in this annex, *are given in italics*.

30.3% within the Midwestern Region (DOE/EIA-0246/86). Excluding these customers from the eligible market leaves 17,202 customers.

Participation. To estimate the participation and expected free ridership, payback acceptance methodology is employed. The estimated payback for the T8 technology without a rebate is 4.4 years for the average commercial customer (11,150 square feet). With a $20 rebate per (4 lamp) luminaire (refer to Incentive section), the payback is improved to 2.7 a. The resulting participation estimates for total customers and free riders, then, are 47.5% and 16.8%, respectively. (Source: Synergic Resources Corp.)

Information obtained from lighting products representatives indicates that the customer reasons for not adopting efficient lighting technologies include a reluctance to change current lighting systems and/or a desire to avoid disruptions in their normal course of business. Lighting professionals currently estimate the T8 technology penetration at 1%. Annual participation estimates are available in the Diffusion section. The evolution of expected participation is listed in Table VII.1.

Rate Class. All customers are evaluated under the standard commercial distribution service rate.

Incentives. Rebates will be offered on a per lamp and one electronic ballast per fixture basis. Based upon both the incentives offered by other utilities for T8 technology and the analysis of the benefits received by participants, the rebates will initially be set at $15.0 per electronic ballast and $1.25 per T8 lamp ($20 for a 4 lamp fixture). Of the available data, no utility offers less than $20 per 4 lamp fixture for the T8 technology. An average customer was assumed to have 194 four (4) lamp fixtures replaced.

Investment. There is no utility investment cost.

Administrative costs. The administrative costs for the program are estimated to be largely dependent upon incremental participation levels (refer to the inspection costs in Other Costs section). It is estimated that a staff of two is necessary to administer the program, monitor the inspections, interface with lighting professionals, offer guidance to customers, and promote the program. Total fixed staff cost is estimated to be $100,000 annually. In addition, the promotion budget is estimated to be $50,000 annually. Promotion will include seminars and other interfacing with the design community, manufacturers, and customers. Other promotional efforts may include targeted mailings or bill inserts, as well as print and trade show advertising.

Other costs. For 1992, the inspection and verification cost is estimated to be $262.50 per participant. The inspection ensures quality installations by the contractors. This cost includes four hours of engineering time, both before and after installation, as well as one additional hour per visit for travel time, data checking and other processing (a total of 10 hours at an assumed rate of $26.25/hour). This cost may increase for larger installations and decrease for other smaller customers. The inspections will include assessing the existing lighting, verifying customer eligibility, projecting the number of lighting replacements and assessing the contractor installation. The expected utility costs are shown in Table VII.2.

Customer cost. There is an annual operation/ maintenance cost, but lighting professionals report that the maintenance cost is about the same as that of the conventional technology. No incremental maintenance cost is modelled.

The customer is responsible for the capital cost of the equipment, as well as any financing that may be required. The incremental customer investment estimate is $11,584.70.

This estimate includes $12,705 total capital cost ($65 for each of the estimated 194 fixtures) less the old luminaire replacement costs (estimated to be $1,120.30 per participant). The expected customer costs are shown in Table VII.3.

Diffusion rate. Total participation is projected for the total system to be 7,821 by the year 2001.

Annual participation estimates are based on the Lawrence-Lawton diffusion estimation methodology and data aggregated by Synergic Resources Corp.

Load Impacts. Load impacts are expected to be realized beyond 2007 since it is assumed that customers will replace the technology in kind.

The commercial lighting load shape is taken from load data available from Electric Power Software and EPRI. The load shape is modified to represent an average commercial customer in the Company's service area. Billing data indicate that the average customer currently uses approximately 245,289 kWh per year and peaks at 92 kW during the summer. Differences between the total system average customer and the Ohio only average customer are minor. An average customer is estimated to have 11,150 square feet (1988 Commercial Saturation Survey). The average load reduction per participant is estimated to be 38% of the customer's lighting load (based on Company results of a T8 demonstration project). This 38% energy savings is applied to 40% of the customers' total load (assumed 40% lighting load portion based on EPRI estimate for typical lighting load).

In addition, the customer may realize a kW reduction in the cooling load during the summer and a heating load increase in the winter. Neither of these impacts are addressed here. These impacts may be included in future evaluations when data become available. *The load impacts are depicted graphically by season in Figures 1 through 4.*

Key areas of uncertainty. There are four key areas of uncertainty for this program. First, the case load impacts assume a specific energy usage and demand per customer for the conventional lighting technology. This estimate may or may not accurately reflect the existing stock.

Second, there is uncertainty surrounding the projected acceptance levels for the program. As well, the extent to which "semi-efficient" lighting has already penetrated the CG&E service area is somewhat uncertain.

Third, there are a number of technological issues associated with the program. Further evaluation is needed to determine the relative cost-effectiveness of different types of lighting technologies. Other technologies may also be viable within commercial markets in the Company's service area.

Fourth, the administrative cost estimates for the program are uncertain. More experience is required with the market to better estimate the amount of effort required to administer this program.

Analyses results. Based on DSManager screening of results, the program is estimated to have a summer peak load impact of 76 MW. Energy reductions are estimated to reach 207,000 MWh annually.

TABLE VII.1. DSM PROGRAM PARTICIPATION DATA

Program identification: Commercial lighting rebate program total system

Total Program Participation

Year	New	Retiring	Cumulative
1992	327	0	327
1993	583	0	910
1994	941	0	1851
1995	1296	0	3147
1996	1445	0	4592
1997	1275	0	5867
1998	914	0	6781
1999	562	0	7343
2000	313	0	7656
2001	165	0	7821
2002	0	0	7821
2003	0	0	7821
2004	0	0	7821
2005	0	0	7821
2006	0	0	7821
2007	0	327	7494
2008	0	583	6911
2009	0	941	5970
2010	0	1296	4674
2011	0	1445	3229

Participant Definition: Number of Customers.

TABLE VII.2. PROJECTED DSM PROGRAM UTILITY COST DATA

Program identification:	Commercial lighting rebate program total system

Program Utility Costs [*]

Year	Incentive payments one-time costs per participant ($)	Annual program administration costs ($/Year)
1992	4074	243340
1993	4278	326060
1994	4492	445980
1995	4716	576150
1996	4952	652500
1997	5200	628170
1998	5460	532590
1999	5733	429200
2000	6019	354090
2001	6320	311530
2002	0	0
2003	0	0
2004	0	0
2005	0	0
2006	0	0
2007	0	0
2008	0	0
2009	0	0
2010	0	0
2011	0	0

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[*] All costs escalated for modelling purposes at 5 percent.

TABLE VII.3. PROJECTED DSM PROGRAM PARTICIPATION COST DATA

Program identification: Commercial lighting rebate program
total system

Program Participation Cost per Participants[*]

Year	Incremental capital costs ($)	Incremental O&M costs ($/Year)
1992	11585	0
1993	12164	0
1994	12772	0
1995	13411	0
1996	14081	0
1997	14785	0
1998	15525	0
1999	16301	0
2000	17116	0
2001	17972	0
2002	0	0
2003	0	0
2004	0	0
2005	0	0
2006	0	0
2007	0	0
2008	0	0
2009	0	0
2010	0	0
2011	0	0

Participant owned equipment useful lifetime: 15 Year

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[*] All costs escalated for modelling purposes at 5 percent.

ANNEX VIII

SAMPLE PROBLEM ILLUSTRATING THE STEP-BY-STEP APPROACH TO DECISION ANALYSIS

VIII.1. Introduction

Throughout the 1980s and early 1990s, a steady increase in SO_2 emissions from the Turkish power sector was accompanied by a growing public concern about the effect of air pollution on human health and agriculture. The Government of Turkey (GOT) undertook several measures to address the air pollution problem. The Environmental Law of 1983 identified broadly defined goals for environmental issues; the Air Quality Control Regulation of 1986 established air quality and emission standards; and, in 1991, the Ministry of Environment was established to develop and monitor compliance with environmental regulations.

The Turkish power sector relies heavily on combustion of poor-quality lignite coal to meet electricity demands. In 1992, lignite-fired power plants represented 30% of the country's installed generation capacity and accounted for roughly 50% of national SO_2 emissions. The Turkish Electricity Authority (TEK) identified five existing lignite-fired power plants as major contributors to the air pollution problem, based on their proximity to areas of dense population, sophisticated agriculture, tourist attractions and archaeological sites. In order to reduce significantly the level of SO_2 emissions and bring these plants into compliance with current air quality standards, TEK and the GOT asked the World Bank to finance a programme to retrofit the five plants with flue gas desulphurisation (FGD).

The World Bank initiated the Turkey Coal Pollution Abatement Project (CPP) to support the GOT's policy of reducing air pollution by focusing on impacts from the power sector. An initial investigation conducted under the CPP confirmed that a local SO_2 problem existed in the area surrounding the Yatagan power plant and that much of this problem could be attributed to the plant. Consultants working for the World Bank noted that Turkish air quality standards for SO_2 had been violated repeatedly during the winter months, frequent complaints of respiratory health problems had occurred in the area since the plant had been commissioned, and farmers had filed an increasing number of lawsuits for compensation for crop losses.

Argonne National Laboratory (ANL) was contracted, under the CPP, to assist the World Bank in developing an economically viable programme for thermal power development and pollution abatement [1]. ANL analysed various power sector options in an attempt to determine the least-cost solution for meeting the power sector's environmental objective of reducing damages from SO_2 emissions at the Yatagan power plant. The methodology employed by ANL consisted of comparing various power sector alternatives on the basis of their total system expansion cost (TSEC), where TSEC is computed as a function of the minimum generating system expansion cost (GSEC) and the discounted environmental damage cost.

Power sector investment options for reducing SO_2 emissions at Yatagan were characterised as a curve defined by the function TSEC = GSEC + (Emissions x Damage Cost) which allowed for comparative display of the options as shown in Figure VIII.1. The various investment options considered under the CPP have a higher GSEC and lower SO_2 emissions than the reference (i.e. business-as-usual) case, causing their respective lines to intersect with the reference case. At the intersect, the option has a TSEC equal to that of the reference case; i.e. the option 'breaks even' with the reference case. The obtained break-even point shows the level of environmental damage cost at which the implementation of the considered option is acceptable economically. The different power sector options can be ranked based on their representative break-even points, with the option having the lowest break-even point being the most cost effective solution for reducing SO_2 emissions. This parametric analysis over a range of specific damage costs allows for comparison of different options while avoiding the uncertainty associated with defining a specific value for SO_2 damage cost.

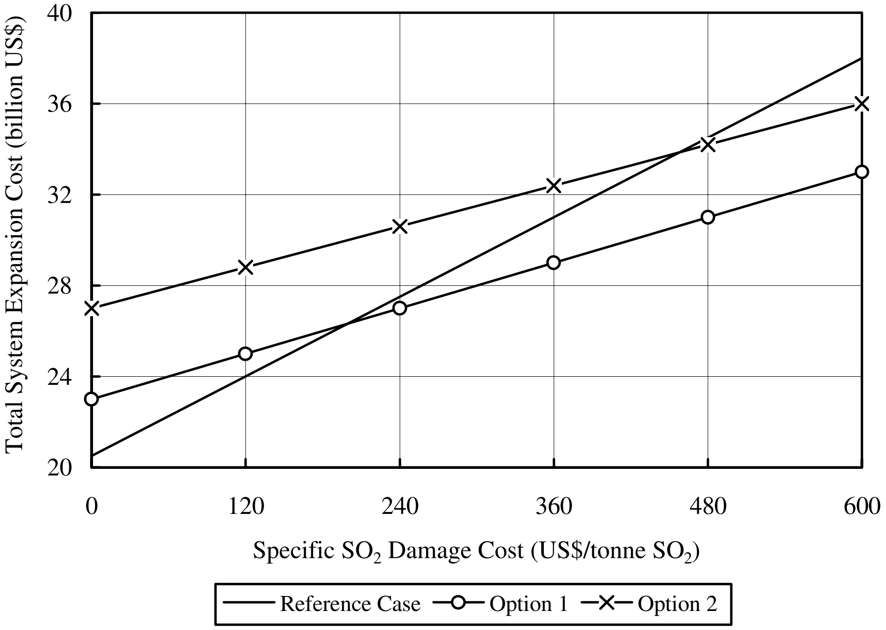

FIG. VIII.1. Ranking of options based on total system expansion cost.

After completing the study of trade-offs between SO_2 pollution reduction and cost for the World Bank, ANL conducted an extended analysis to examine a broader range of impacts [2]. The remainder of this annex provides a brief overview of the extended analysis as an example of the step-by-step approach to decision analysis.

VIII.2. Methodology for the extended analysis

Three main models are utilised in conducting the extended analysis: WASP-III, the IMPACTS Module of the Energy and Power Evaluation Program (ENPEP), and the Decision Analysis Module (DAM). Figure VIII.2 shows how these models are integrated to perform the analysis. The first step is to run WASP to determine the least-cost system expansion plan for each power sector investment option. WASP uses cost-optimisation techniques to develop an installation schedule that meets electric demand as well as system constraints at minimum generating system expansion cost [3]. In the sample problem, generating system expansion cost is expressed as net present value (in 1992 U.S. dollars) with a discount rate of 10%.

The next step is to transfer the WASP installation schedule and other relevant data such as plant capacity, heat rate, and fuel consumption to the IMPACTS module, which calculates environmental residuals and resource requirements associated with a given electric generation expansion plan [4]. In addition, IMPACTS allows: (1) analysis of the environmental and economic impacts of regulatory actions, calculating the expected emission reductions for each power station and the entire electric system; and (2) calculation of the incremental environmental control cost incurred to bring about these reductions.

The results from the WASP and IMPACTS modules are transferred to the DAM software for use in comparing and ranking alternative investment scenarios. DAM is a tool for comparing and evaluating costs, environmental impacts and other important measures of performance associated with electric system expansion planning [5, 6].

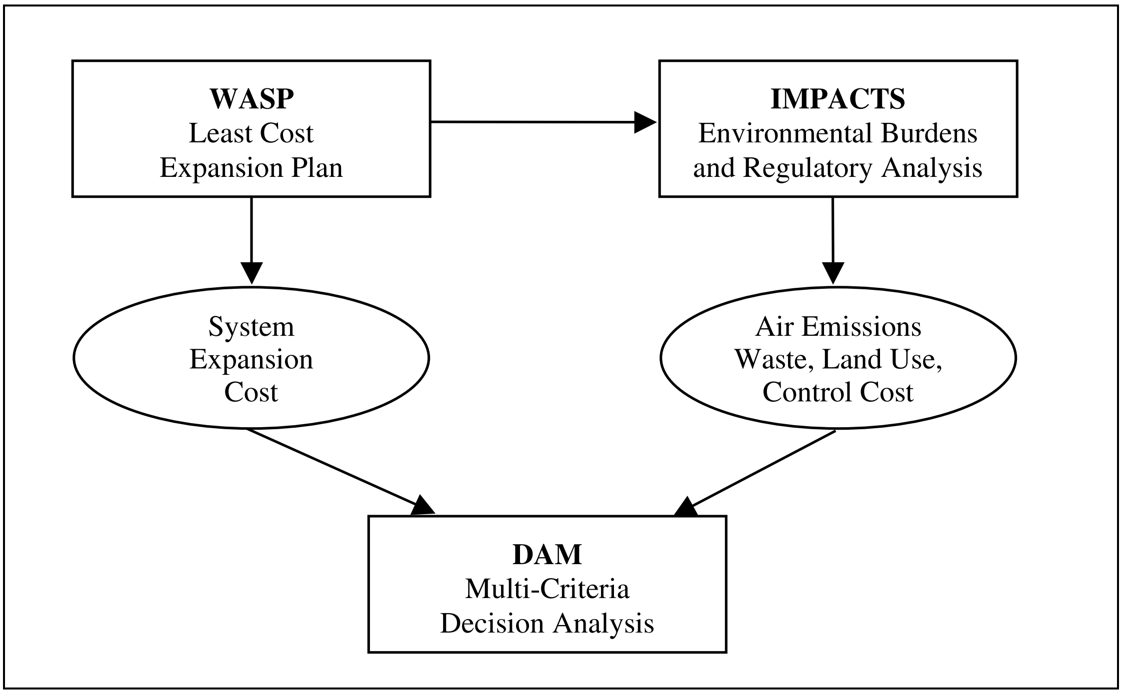

FIG. VIII.2. Schematic representation of the extended analysis.

Key characteristics of the methodology include: (1) decision analysis foundation; (2) potential to use intervals for trade-offs among measures of performance, rather than precise values, and (3) a convenient user interface that provides rapid feedback about whether a particular factor is important.

VIII.3. Specify objectives and measures

The objective of the sample problem is to illustrate a methodology that could be used to determine the least-cost power sector alternative for reducing adverse environmental impacts in a country or region. Because of the demonstrative purpose of the sample problem it was decided not to make great efforts to obtain comprehensive data about all of the environmental impacts. Instead, the analysis takes into account only air pollution, waste generation and land use.

The following criteria were taken into account for evaluation of alternatives:

- Total system expansion cost (direct economic cost) over the period 1992-2010, consisting of the capital cost, fuel cost, operation and maintenance cost, energy-not-served cost, and salvage value of the expansion candidates commissioned during the planning period,
- Annual air pollution from emissions of SO_2, NO_x, CO, CO_2, methane, nonmethane volatile organic compounds (NMVOC),
- Annual waste generated by power plants, and
- Land used for the power plants.

VIII.4. Identify candidate expansion strategies

Results of the World Bank CPP formed a basis for the extended analysis conducted by ANL. In reviewing the Turkey CPP within the World Bank, experts generally agreed that a local air pollution problem existed as a result of SO_2 emissions from the Yatagan power plant. However, the reviewers pointed out that retrofitting Yatagan with FGD was not necessarily the least-cost solution. A number of power sector options were suggested as possible alternatives to FGD.

The following options were considered in the analysis:

1. Retrofit Yatagan with FGD,
2. Replace Yatagan with a new combined-cycle plant,
3. Replace Yatagan with a new imported coal plant,
4. Derate capacity and change the merit order of Yatagan to account for plant shutdown or reduced operation when air quality standards are exceeded, and
5. Shut down Yatagan prior to the year 2010.

A reference scenario was established with no FGD retrofits of existing plants, but requiring FGD on all newly constructed coal-fired power plants. The costs and technical characteristics also reflected that electrostatic precipitators are installed on all existing and candidate coal-fired power plants. The reference scenario provides an estimate of expected system costs and environmental burdens in the absence of any additional measures to reduce pollutant emissions from Yatagan.

VIII.5. Describe possible impacts for each strategy

The aggregated data for all decision alternatives is presented in Table VIII.1. Since decisions made for the Yatagan power plant influence the whole electric system in Turkey, the data used in the analysis takes into account not only the Yatagan power plant but all facilities in all regions of Turkey. Thus, it is not surprising that, for example, the ‘Combined Cycle’ alternative is characterised by significant emission of SO_2.

VIII.6. Evaluate impacts of each strategy

In the extended analysis performed by ANL, a number of studies were conducted using different intervals of impact cost. Table VIII.2 shows the set of illustrative values of environmental impacts chosen for use in the sample problem.

TABLE VIII.1. AGGREGATED DATA FOR DECISION ALTERNATIVES (YEARS 1992 - 2000; DISCOUNT RATE 10% PER YEAR)

Option	Cost* (U.S. $)	Particulates (tonnes)	SO_2 (tonnes)	NO_x (tonnes)	CO (tonnes)	NMVOC* (tonnes)	Methane (tonnes)	CO_2 (tonnes)	Waste (tonnes)	Land Use* (m^2)
Reference	2.0589e+10	1.1180e+06	1.6948e+07	3520497	176560	23562	8821	5.11e+08	1.3878e+08	5547400
FGD	2.0907e+10	1.1884e+06	1.5536e+07	3520920	176627	24243	8824	5.11e+08	1.3886e+08	5799400
CombCycle	2.0962e+10	1.0904e+06	1.5638e+07	3286925	164891	22006	8237	4.91e+08	1.3176e+08	5615400
Import Coal	2.1197e+10	1.4016e+06	1.5802e+07	3399318	167388	33046	8462	5.03e+08	1.3395e+08	5608400
Der. 33%	2.0752e+10	1.0957e+06	1.6272e+07	3465027	169388	23209	8689	5.06e+08	1.3707e+08	5598400
Der. 66%	2.1084e+10	1.1382e+06	1.5646e+07	3439751	172668	23047	8626	5.04e+08	1.3772e+08	5598400
SD 1993	2.1328e+10	1.1227e+06	1.4983e+07	3285361	164900	22015	8237	4.96e+08	1.3388e+08	5707400
SD 1996	2.1238e+10	1.1604e+06	1.5522e+07	3339457	167517	22361	8368	5.00e+08	1.3550e+08	5707400
SD 1999	2.1064e+10	1.1354e+06	1.6015e+07	3647393	182900	24406	9138	5.16e+08	1.4149e+08	5707400
SD 2005	2.0780e+10	1.1472e+06	1.6610e+07	3560725	178512	23822	8919	5.13e+08	1.3949e+08	5707400
SD 2008	2.0684e+10	1.1768e+06	1.6794e+07	3506295	175985	23447	8778	5.10e+08	1.3810e+08	5707400

*Notes:

Land Use	Cost of land is not discounted. It is assumed that all land is purchased in 1992 and paid in 1992 U.S. dollars.
Cost	Direct economic cost.
NMVOC	Nonmethane volatile organic compounds.

List of Options:

Reference	The Reference Case Scenario
FGD	Retrofit Yatagan with Flue Gas Desulphurisation
CombCycle	Yatagan Replaced with a Combined Cycle Plant
Import Coal	Replace Yatagan with a New Imported Coal Plant
Der. 33%	Derate Capacity of Yatagan by 33%
Der. 66%	Derate Capacity of Yatagan by 66%
SD 1993, etc.	Shut Down Yatagan in the indicated year

TABLE VIII.2. ILLUSTRATIVE VALUES FOR ENVIRONMENTAL IMPACTS

Factor	Unit	Minimum Cost (US $)	Maximum Cost(US $)
Particulates	1 tonne	50	60
SO_2	1 tonne	360	410
NO_x	1 tonne	150	180
CO	1 tonne	10	50
NMVOC	1 tonne	100	800
Methane	1 tonne	20	90
CO_2	1 tonne	0.3	1.4
Waste	1 tonne	2	4
Land Use	10,000 m^2	1000	3000

VIII.7. Comparison of alternative strategies

Applying traditional decision methodology to analyse the power sector options considered in the sample problem would require exact estimates of the costs of environmental damages caused by air pollutant emissions, the cost of waste disposal, and also the cost of land. If the exact costs for all of these factors were known, one could calculate the ‘total cost’ of every decision alternative and rank the power sector options by their total costs. However, the problem is that the cost estimates of environmental damage per tonne of any pollutant differ significantly. Usually, one can estimate only an interval containing the ‘true’ value.

The ‘interval’ decision methodology was developed especially for decision problems involving imprecise trade-offs. The DAM software was used in applying the interval decision methodology to analyse power sector options in the sample problem. The illustrative values for environmental impacts were applied to the aggregate data for decision alternatives to generate the final ranking of alternatives shown in Table VIII.3. According to this table, the ‘FGD’ and ‘Combined Cycle’ alternatives are better (in terms of total cost) than any other alternative whatever the ‘true’ environmental costs are within the specified ranges. Alternatives ‘Import Coal’ and ‘Shut Down in 1999’ are worse than any other alternative. The question mark in the cell ‘FGD’ versus ‘Combined Cycle’ means that, for some estimates of the costs within the specified ranges, the ‘FGD’ alternative has lower total cost than the ‘Combined Cycle’, and for some other estimates within the same ranges it has higher total cost. That is, further investigation is warranted to decide which of these two alternatives is best.

VIII.8. Conclusions

This example has briefly illustrated one method for formally including environmental impacts as well as costs in the decision evaluation. An attractive feature of the approach is that it does not require precise trade-offs between all impacts; instead, it makes use of reasonable intervals for trade-offs. In this particular study, significant effort was devoted only to characterising the costs of different expansion plans and to the sulphur dioxide emissions. For a real application, significant effort needs to be devoted to all the steps outlined earlier in Chapter 4.7.4, namely:

I. Specify objectives and measures
  - What is important to this problem?
  - How might achievement with respect to each objective be measured?
  - Who should be involved in the specification of objectives?

II. Identify candidate expansion strategies
  - Which alternatives emphasise different objectives specified in step I?
  - Note that until all objectives have been specified, a reasonable set of alternatives cannot be identified, and much effort can be wasted on characterising alternatives that ultimately turn out to be unimportant.

TABLE VIII.3. RANKING MAP OF THE ALTERNATIVES

Option	ID	A	B	C	D	E	F	G	H	I	J	K
FGD	A		?	+	+	+	+	+	+	+	+	+
CombCycle	B	?		+	+	+	+	+	+	+	+	+
Der. 33%	C	-	-		?	+	+	+	+	+	+	+
SD 1993	D	-	-	?		+	+	+	+	+	+	+
Reference	E	-	-	-	-		?	+	+	+	+	+
Der. 66%	F	-	-	-	-	?		+	+	+	+	+
SD 2008	G	-	-	-	-	-	-		?	+	+	+
SD 1996	H	-	-	-	-	-	-	?		?	+	+
SD 2005	I	-	-	-	-	-	-	-	?		+	+
Imp. Coal	J	-	-	-	-	-	-	-	-	-		?
SD 1999	K	-	-	-	-	-	-	-	-	-	?	

‘+’ alternative in the column has higher total cost than alternative in the row
‘-’ alternative in the column has lower total cost than alternative in the row
‘?’ interval estimates of environmental damage costs are too broad to determine which of the two alternatives has higher total cost

III. Describe possible impacts for each strategy
- Can models be used to estimate the levels of impacts in understandable, but not value-laden terms, such as quantities emitted?

IV. Evaluate impacts for each strategy
- What are the relative values for different levels of achievement with respect to each objective and with respect to the several different objectives?
- Whose value judgements should be assessed?

V. Analyse and compare alternative strategies
- How robust is the favoured option?
- If the favoured option emphasises a particular technology, does the next most favoured option also favour that technology or a completely different technology?

In the final analysis, one must examine how worthwhile it is to make these considerations explicit instead of implicit. Explicit analysis typically involves hard work, but the insights and problem understanding that result usually are worth the effort.

REFERENCES TO ANNEX VIII

[1] KORITAROV, V.S., CONZELMANN, G., HAMILTON, B.P., BUEHRING, W.A. AND CIRILLO, R.R., Turkey Coal Pollution Abatement Project: An Integrated Economic and Environmental Evaluation of Generating System Expansion Options, Argonne National Laboratory, Argonne, Ill. (1993).

[2] PODINOVSKI, V.V., KORITAROV, V.S., BUEHRING, W.A. AND CONZELMANN, G., Analysis of the Power Sector Options in Turkey Using the Decision Support System MCITOS, Argonne National Laboratory, Argonne, Ill. (1993).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electric Generating Systems A Guidebook, Technical Report Series No. 241, STI/DOC/10/241, Vienna (1984).

[4] HAMILTON, B.P. CIRILLO, R.R. AND BUEHRING, W.A., "ENPEP: An Integrated Approach to Energy Planning", in Energy, Environment and Information Management (Proc. Int. Symp. on Energy, Environment and Information Management), pp. 3.21-3.29 Argonne National Laboratory, Argonne, Ill. (September 1992).

[5] PODINOVSKI, V.V., Decision Methodology Used by MCITOS, Argonne National Laboratory, Argonne, Ill. (1993).

[6] PODINOVSKI, V.V., MCITOS: The User's Guide, Argonne National Laboratory, Argonne, Ill. (1993).

GLOSSARY

TERM	DEFINITION FOR PURPOSES OF THIS BOOK
Abatement costs	Costs which arise from preventing discharges to the environment. Include both control costs and the cost of "turning off" the emitters, that is the lost output that results from shutting down the source of emissions.
Adders	Estimates of the monetary value of damage imposed upon society by each additional ton of a particular pollutant. In theory, when these values are added to the direct cost of resources under planning consideration, resources with the lowest total social cost can be identified.
Adjusted load forecast	Forecast of the peak power and energy demand which the utility would normally generate or purchase in order to meet customer demands. Refers to the forecast obtained by subtracting the Efficiency Improvement, the Load Shifting and the Non-Utility Generation from the Base Forecast.
Base load	That part of total demand that does not vary over a given period (day, month, year).
Biodiversity	Refers to the variety and variability among living organisms and the ecological complexes in which they occur. Diversity can be defined as the number of different items and their relative frequencies.
Biomass	Organic, non fossil material of biological origin, a part of which constitutes an exploitable energy resource. Although the different forms of energy from biomass are always considered as renewable, it must be noted that their rates of renewability are different. These rates depend on the seasonal or daily cycles of solar flux, the vagaries of climate, agricultural techniques or cycles of plant growth, and may be affected by intensive exploitation. However, as a statistical average, they may be considered as renewable yearly.
Case study	Detailed analyses (economic, environmental) and planning studies to analyse specific problems.
Combined cycle	Electricity generating system comprising a gas-turbine generator unit whose exhaust gases are fed to a waste-heat boiler, which may or may not have a supplementary burner, and the steam raised by the boiler is used to drive a steam turbine generator.
Constraint	Factor which may limit or influence the solutions of a problem, e.g. limit on atmospheric emissions.
Consumer price index (retail price index)	An index number of prices of goods which is often referred to as the 'cost of living index'. It measures relative changes in the prices of a specified set of consumer goods which would be bought by the average household on a regular basis. The weights are based on information from the government's survey of family expenditure to ensure that it relates to present day buying patterns. Goods representing larger proportions of expenditure will then be given more significant weights in the index.
Cost of unserved energy	Cost associated with the average energy that will be demanded but not served during a specified period due to, for example, inadequate available generating capacity or breakdown of transmission lines.

Cost-benefit analysis	Method for examining and accounting the positive effects (benefits) and negative effects (costs) of undertaking an action (More details in chapter 1.4).
Damage cost	Monetised value of detrimental impacts which accrue to society from the activities of producers and consumers. A related term, benefit, refers to the monetary value of positive impacts.
Damage function approach	A step-by-step approach to valuing environmental damages, starting from emissions, to concentrations, to impacts, to damages.
Decision analysis	Decision-making process that provides a mathematical framework by which a large set of strategies can be evaluated for a number of uncertain parameters.
Decommissioning	The process of closing down and putting a facility into a safe state after its useful life has come to an end.
Demand analysis	Analysis of past and/or present and/or future energy consumption under certain conditions (GDP, industrial development, etc.).
Demand side management (DSM)	Activities which encourage consumers to modify patterns of electricity usage, including the timing and level of electricity demand, e.g. use of compact fluorescent lighting.
Direct costs	The direct capital costs of a power plant include those costs associated with the purchase and installation of plant components. It consists of the factory equipment costs and the site installation costs. The latter include the site labour costs (which in turn include both the wages and the benefits for the labour force) and the costs of installation materials (e.g. welding material, reinforcement rods, wiring).
Discount rate	Interest rate reflecting the time value of money that is used to convert benefits and costs occurring at different times to equivalent values at common time.
Econometric model	Model that uses statistical relationships between past electricity sales and actual major historical factors, such as economic activity and prices, to forecast future electricity sales.
Ecosystem	The interacting synergism of all living organisms in a particular environment; every plant, insect, aquatic animal, bird, or land species that forms a complex web of interdependency.
Electricity intensity	Amount of electricity consumed by customers (in kilowatt-hours) per constant monetary unit of real Gross Domestic Product (GDP).
Electricity system planning	Overall process of analysing, assessing and comparing alternative strategies for electricity system expansion in support of decision making (More details in chapter 1.4).
End-use modelling	Energy demand forecasting approach based on the end uses of electricity and the factors that influence such end uses, such as electricity consumption, end-use efficiencies, turn-over of appliance stock, etc.

Energy conservation	Reduction of energy inputs for achieving a desired effect. Includes such measures as the rational use of energy and substitution of energy forms and processes by more suitably adapted ones, e.g. a wall insulation can reduce the fuel consumption for heating although it maintains the same level of comfort.
Expansion planning	Planning aimed at identifying the schedule of plant additions and network development over a certain period of time which yields the optimum benefits while satisfying the projected electricity demand with a certain margin of reserve and respecting certain foreseeable constraints.
External dose	Measure of the radiation received following an irradiation by a radioactive source outside the body.
Externality	Economic consequences resulting as an unintended by-product of an industrial activity that accrue to someone other than the parties involved in the activity. Where these consequences are detrimental, they are called external costs; where these consequences are positive, they are called external benefits.
Fuel (energy) chain analysis	Aims toward investigating in detail all aspects of different energy chains and comparing them. Approach that considers the energy and material flows, and emissions, wastes and residuals within the entire chain from the resource level to the delivered energy service level. Allows to account and compare environmental aspects of alternative options that supply similar services to the final user.
Full cost pricing	A pricing rule where firms add a net profit margin onto unit costs where the calculation for the latter includes all costs.
Global climate change	Potentially disruptive changes to the Earth's climate caused by rising absorption of the sun's heat. The sun's heat is captured within the Earth's atmosphere by so-called "greenhouse gases," such as water vapour, carbon dioxide, methane, and nitrous oxide. Atmospheric concentrations of these gases are rising due to human activities, including combustion of fossils fuels and deforestation.
Greenhouse gases	Those gases, such as water vapour, carbon dioxide, troposphere ozone, nitrous oxide, and methane, that are responsible for keeping the Earth's surface warmer than it would otherwise be. These gases are transparent to solar radiation but opaque to long wave radiation. The latter radiation, which would otherwise escape to space, is trapped by greenhouse gases within the lower levels of the atmosphere. Their action is similar to that of glass in a greenhouse.
Impact assessment	Evaluation of the physical or socio-economic effect of a given activity. Examples of physical impacts are changes in crop yields, human health, and recreation resources. Examples of socio-economic impacts are changes in aesthetics, noise nuisance, and employment conditions.
Impact pathway methodology/damage function methodology	A step-by-step methodology to valuing environmental damages, starting from the origin of a pollutant, i.e. emission, to concentration, to impact, to damage.
Information asymmetries	What every agent knows is not known by every other agent, and vice versa.

Integrated resource planning (IRP)	A technical planning process that attempts to put supply side and demand side alternatives on the same level playing field in an integrated analysis, with extensive involvement by interested and affected parties other that utility stockholders.
Interested and affected parties	All parties involved in and affected by policies in the power sector. Ranges from producers on through regulators, investors, non-governmental organisations, consumer groups, members of the public, environmental groups, etc.
Internal dose	Measure of the radiation received or 'absorbed' following an irradiation by radioactive sources taken into the body by inhalation or ingestion or through the skin.
Internalising an externality	Creating social conditions where the damages (or benefits) from production and consumption are taken into account by those who produce these effects. These social conditions can be created by government regulation, a tort system, bargaining between private parties, or other policy and institutional arrangements. Benefits and damages can exist even when all externalities have been internalised.
Interruptible loads	Loads that can be interrupted in the event of a capacity or energy deficiencies on the supplying system.
Least cost planning (LCP)	Aims toward scheduling technically feasible electricity generation expansion paths in such a way that the total system costs, including investments, operating and maintenance and fuel, are minimised subject to certain constraints (More details in chapter 1.4).
Lentic environment	Refers to still waters (as lakes, ponds, or swamps).
Levelised cost	Rate which must be charged per unit of product to recover all expenditures incurred during construction, operation and decommissioning of a plant.
Life cycle analysis	Economic and environmental analysis for the whole life cycle of a technology, starting from construction through the operation phase, up to the end of operation and decommissioning. Includes activities associated with production and processing of fuels and construction materials.
Load forecast	Estimate of electric power demand at some future time, in terms of maximum level and time distribution (e.g. hourly) of demand.
Load management	Efforts to change electricity demand patterns to reduce cost; includes actions by consumers, utilities, or public agencies to reduce, shift, or decrease demand at selected time. Any effort to control loads by economic incentives, direct interventions, or new technology. Shifting load from peaks to valleys, or simply shaving the peak, defers capacity additions and transfers load from high cost, inefficient peaking generation to more economically efficient base-load units.
Load shifting	Efforts to move loads from peak periods (periods of relatively high system demand) to off-peak periods (periods of relatively low system demand). Reduces the peak power demand by shifting some electricity demand from periods of high use to periods of low use.
Lotic environment	Refers to actively moving water (as rivers).

Marginal cost	The increase in the total costs of an enterprise caused by increasing its output by one extra unit. Marginal cost pricing is setting the price of an item equal to the cost of producing one extra unit of the item. Marginal cost represents the opportunity cost, or the total sacrifice to society, for producing an item. Long-run marginal cost is the cost of meeting an increase in consumption, sustained indefinitely into the future, when needed capacity adjustments are possible. In the long run, an increase in demand will result in a corresponding increase in the operating costs as well as in the capacity costs.
Mitigation action/option	Action taken to reduce the degree or intensity of pollution. Examples include; "creative conservation" projects to re-create wildlife habitats destroyed during construction, liming lakes to offset acidification, planting trees to absorb carbon dioxide or building defences against sea level rise.
Mitigation costs	Arise when environmentally harmful or potentially harmful activities are permitted but action is taken to reduce or compensate for the consequences.
Multi criteria decision-aiding methods	Methods that allow to arrive at a decision in a situation where several criteria (often conflicting) have to be considered.
Network analysis	Calculates the flows and impacts involved for an energy network providing a demanded energy service. Allows the evaluation of different technology paths according to multiple criteria: cost, energy balance, environmental pollution, resource consumption, etc. (More details in chapter 3).
Non-utility generation	Electrical generation owned and operated by electricity producers other than an utility, i.e. private and municipal utilities and private power owners (More details in Section 4.4.3.6).
Operation and maintenance (O&M) costs	All non-fuel costs, such as the direct and indirect costs of labour and supervisory personnel, consumable supplies and equipment, outside support services and (if applicable) moderator and coolant make-up and nuclear liability insurance. O&M costs are made up of two components: fixed costs (those that are invariant with the electrical output of the plant) and variable costs (those non-fuel costs that are incurred as a consequence of plant operation, e.g. waste disposal costs).
Operational planning	Focuses on the proper management, running and maintenance of the energy equipment or energy system. In most cases, it requires detailed analyses on a component level and with a fine temporal resolution (More details in chapter 3.3).
Opportunity costs	A cost term, which equals the cost of an economic activity foregone by the choice of another activity. It is dependent on the existence of an alternative use. Arise from the difference between a situation corresponding to the optimum production plan and the present situation.
Parameter variations	Performed by modifying either a scenario parameter or a strategy measure for all cases considered. Variations of a scenario parameter allow to compare the capability of different strategies to cope with different evolution of exogenous factors such as oil prices on international markets. Variations of strategy measures allow to identify the optimum for a given measure.

Payback phenomenon	Profitability criterion which describes the process by which the total revenue connected with the operation of an installation, after deduction of all costs including taxes, is equal to the amount of investment required for the purchase, construction and commissioning of the installation.
Peak load	Maximum load which must be provided by a supply network during a given time period (e.g.: day, month, year) to satisfy the peak demand.
Planning	Systematic assembly and analysis of information about energy supply and demand and presentation of this information to decision-makers. Dynamic process that is repeated periodically and adjusted to changing conditions.
Policy	Principle of actions adopted by decision makers.
Policy oriented planning	Analysis aimed at providing information for the setting of regulatory frameworks, or for the establishment of legislation, standards, taxes, subsidies, etc.
Polluter pays principle	The principle that those causing environmental harm shall bear the cost of its remedying.
Pollution control technologies	Chemical and physical methods to lessen discharges of most pollutants. Specific means for removing pollutants from emissions are abatement technologies such as flue-gas desulphurisation, electrostatic precipitators, scrubbers, etc..
Precautionary principle	Takes into account the existence of an uncertainty by considering its occurrence or by assigning to it an envelope value, e.g. measures have been taken to limit the use of CFC gases as a precaution against the destruction of the ozone layer.
Regulation	The supervision and control of the economic activities of private and arm-length public enterprises by government in the interest of economic efficiency, fairness, health, and safety. Regulation may be imposed simply by enacting laws and leaving their supervision to the normal processes of the law, by setting up special regulatory agencies, or by encouraging self-regulation by recognising, and in some cases delegating powers to, voluntary bodies.
Residual discharges	Discharges containing pollutants which remain after compliance with all existing regulations.
Right-of-way/transmission or distribution route	The area required for running an overhead or an underground transmission line.
Risk attitude	Attitude that leads to a decision for which there is a range of possible outcomes that could flow from it.
Robust solution	Solution which provides the highest benefits in all investigated scenarios.
Scenario	Picture of future energy demand and supply. A scenario is not a forecast but represents one possibility amongst many possible futures.
Sensitivity analysis	A method of analysis which introduces variations into such factors as simulation period, estimated coefficients, and explanatory variables in a model to examine what effect they have upon the explained variable.

Separation of expenditures and benefits	Two parties are involved. The first party is responsible for making an investment of some kind while the other party uses the equipment installed by the investment. The equipment selection is based on the criterion of minimising the investment costs for the first party, regardless of the investment's economic efficiency from the viewpoint of the second party, for example with regard to operation costs (including fuel).
Social and/or environmental impact	Any alteration of the physical, chemical and biological characteristics of the environment caused by any form of matter or energy as a result of human activities which directly or indirectly affects human health, safety and population welfare, the social and economic activities, the biota, the sanitary and aesthetical conditions of the environment and the quality of the environmental resources.
Social benefit/cost	Represent the increase or decrease in individual welfare resulting from a particular activity.
Source term	Denotes information about the actual or potential release of radiation or radioactive material from a given source, which may include further specifications, e.g. the composition, the initial amount, the rate and the mode of release of the material.
Strategic planning	Leads to identifying the investments or actions that are necessary to meet the long term future energy service requirements best (More details in Section 3.3).
Strategy	Set of actions and measures that can be decided by policy makers to solve the problems within a given scenario.
Supply side management (SSM)	Technologies or programmes that pertain to the generation of electricity.
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It means the balancing of economic, social, environmental and technological considerations, as well as the incorporation of a set of ethical values.
Switching station	An electrical installation for the selective connection and disconnection of the lines of a network and of consumer installations by means of switching gear (circuit-breakers and disconnecting switches).
Tariffs	Unified price structure proposed in demarcated areas for the same group of consumers (for example, domestic, agricultural or tertiary sectors) or in the same fields of use (for example, transport, lighting, cooking, heating). The configuration of tariff structures differs according to country, product or service. For electricity, gas and district heating, either a rating related solely to energy, for example, rating for small users, can be distinguished, or a two part rating, that is to say, taking into account a fixed premium (related to power, number of rooms, cultivated hectares, etc.) and the quantity of energy consumed, with the distinction of peak period, off-peak period or seasonal consumption.
Transaction costs	Costs which are apt to appear because a market for each product, at each point of space, at each moment of space, and for each conceivable state of nature does not exist.

Value judgement	A statement that can, in general, be reduced to the form ‘X is good (bad)’. In turn, such statements are analysed in different ways by different philosophers. Some would say ‘X is good’ means ‘I like X’; for others it means ‘I like X and you should like it too’, and so on. The term value judgement causes extensive confusion in economics. Common misconceptions are that it is synonymous with ‘a matter of opinion’, whereas ‘in my opinion it will rain tonight’ is a positive statement of predictive form and has no value judgement involved in it.
Waste management	All activities, administrative and operational, involved in the handling, treatment, conditioning, transport, storage and disposal of wastes.
Willingness to pay	The valuation placed by an individual on a good or service in terms of money. The valuation is in two parts: ‘market price and consumer surplus’, if any. ‘Willingness to accept’ is the analogous approach of finding out how much people are willing to accept in the way of compensation to put up with the loss.

RELATED MATERIAL

BRACKLEY, P., Energy and Environmental Terms: A Glossary, Gower Publishing Co., Brookfield, VT (1988).

COUNCIL OF ACADEMIES OF ENGINEERING AND TECHNICAL SCIENCES, The Role of Technology in Environmentally Sustainable Development, Kiruna, Sweden (1995).

DE ALMEIDA, A., ROSENFELD, A., ROTURIER, J. AND NORGARD, J., Integrated Electricity Resource Planning, NATO ASI Series, Series E: Applied Sciences-Vol. 261, Kluwer Academic, Dordrecht, The Netherlands (1994).

INTERNATIONAL ATOMIC ENERGY AGENCY, Economic Evaluation of Bids for Nuclear Power Plants: A Guidebook, Technical Report Series No. 269, Vienna (1986).

INTERNATIONAL ATOMIC ENERGY AGENCY, Energy and Electricity Demand Forecasting for Nuclear Power Planning in Developing Countries: A Reference Book, IAEA-TECDOC-470, Vienna (1988).

INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electrical Generating Systems: A Guidebook, Technical Report Series No. 241, Vienna (1984).

INTERNATIONAL ATOMIC ENERGY AGENCY, Financing Arrangements for Nuclear Power Projects in Developing Countries: A Reference Book, Technical Report Series No. 353, Vienna (1993).

PEARCE, D., The MIT Dictionary of Modern Economics, The MIT Press, Cambridge, MA (1992).

TENNESSEE VALLEY AUTHORITY, Energy Vision 2020 — An Integrated Resource Plan and Programmatic Environmental Impact Statement, vol. 1, Chattanooga, TN (1995).

UNITED STATES DEPARTMENT OF ENERGY, ENERGY INFORMATION ADMINISTRATION, Electricity Generation and Environmental Externalities: Case Studies, DOE/EIA-0598, Washington, D.C. (1995).

UNITED STATES DEPARTMENT OF ENERGY, ENERGY INFORMATION ADMINISTRATION, Emissions of Greenhouse Gases in the United States, DOE/EIA-0573, Washington, D.C. (1994).

WESTERN SOUTHWESTERN/SOUTHEASTERN AREA POWER ADMINISTRATIONS, Resource Planning Guide, vol. II: Fast Track Workbook, Denver, CO (1993).

WORLD ENERGY COUNCIL, Energy Dictionary 1992, Paris (1992).

BIBLIOGRAPHY

ADLER, K., ERDMANN, G., KAPPEL, R. AND STAUB, P., An Energy Scenario Generator Model for the People's Republic of China: Description of the ESG Model, ZENCAP Working Papers No. 19, Institüt fur Wirtschaftsforschung, Zurich (1985).

ALLEN, P.T., FOUGUET, R. AND MUURLINK, O., Review of Information Relevant to Compensation for Catastrophic Events, Study Report R1/93/PSY/001, Robens Institute of Health and Safety, University of Surrey, Guildford, UK (1993).

AMANN, M., BERTOK, I., COFALA, J., DÖRFNER, P., GYÁRFÁS, F. AND SCHÖPP, W., "Impacts of Energy Scenarios on Regional Acidification", in Local and Regional Energy Related Environmental Issues - Case Studies, pp. 291-317, World Energy Council, London (1995).

ANDREANI-AKSOYOGLU, S. AND KELLER, J., "Influence of Meteorology and Other Input Parameters on Levels and Loads of Pollutants Relevant to Energy Systems: A Sensitivity Study", in Caussade, B., Power, H. and Brebbia, C. (Eds.), Air Pollution IV: Monitoring, Simulation and Control, pp. 769-778, Computational Mechanics Publications (1996).

BAHN, O., FRAGNIERE, E. AND KYPREOS, S., "Swiss Energy Taxation to Curb CO_2 Emissions", in Proc. of 1996 European Environment Conference (16-17 September 1996, Leeds, UK), pp. 1-6, ERP Environment, Shipley, West Yorkshire (1996).

BAKER, A. AND GREGORY, K., "External Costs of Power Generation - How Reliable are They?", UK CEED Bulletin, Issue 45 (July - August 1994).

BALL, D.J., ROBERTS, L.E.J. AND SIMPSON, A.C.D., An Analysis of Electricity Generation Health Risks a UK Perspective, University of East Anglia (1993).

BAUERSCHMIDT, R., Kernenergie oder Sonnenenergie, Beck, München (1985).

BELL, D.E., KEENEY, R.L. AND RAIFFA, H., Conflicting Objectives in Decisions, International Institute for Applied Systems Analysis, Wiley, Chichester (1977).

BERNDT, E.R. AND FIELD, B. (Eds.), Modeling and Measuring Natural Resource Substitution, MIT Press, Cambridge, MA (1981).

BERSEN, E., "Integrated Energy and Environmental Planning at Regional and Local Level", Proceedings of 15th Congress of the World Energy Council, Madrid (1992).

BONNEVILLE POWER ADMINISTRATION, UNITED STATES DEPARTMENT OF ENERGY, Final Environmental Impact Statement Resource Programs, DOE/EIS-0162 (February 1993)

BROWN, R.V., KAHR, A.S. AND PETERSON, C., Decision Analysis for the Manager, Holt, Rinehart and Winston, New York (1974).

CARLEVARO, F. AND SPIERER, C., Dynamic Energy Demand Models with Latent Equipment, European Economic Review 23 (1983).

CAVALLO, J., HEMPHILL, R. AND VESELKA, T., IRP Methods for Environmental Impact Statements of Utility Expansion Plans, Proc. Int. Symp. on Energy, Environment and Information Managemen, (Argonne National Laboratory, USA), Argonne, IL (September 1992).

CHAPPELL, T.E. AND JOYCE, J. S., Environmental Aspects of the Killingholme Combined Cycle Power Plant, IMechE, London (1990).

CLAUSS, L. AND CHANG, D., "Integrated Planning: A Baseline Development Perspective", U.S. Department of Energy, Second Annual EM Cost Management Conference, San Francisco, CA (December 8, 1994).

CLINE, W.R., Estimating the Benefits of Greenhouse Warming Abatement, Institute for International Economics, Washington, D.C. (1991).

CLINE, W.R., The Economics of Global Warming, Institute for International Economics, Washington, D.C. (1992).

CO-OPERATIVE PROGRAMME ON ENERGY AND DEVELOPMENT (COPED), Diagnosis on Energy Systems in Developing Countries, J. Girod (Ed.), Office for Official Publications of the European Communities, Luxembourg (1991).

CO-OPERATIVE PROGRAMME ON ENERGY AND DEVELOPMENT (COPED), Key Issues Facing the Electricity Systems of Developing Countries, de Oliviera, A. (Ed.), Office for Official Publications of the European Communities, Luxembourg (1991).

CO-OPERATIVE PROGRAMME ON ENERGY AND DEVELOPMENT (COPED), Electricity System Performance: Options and Opportunities for Developing Countries, de Oliviera, A. (Ed.), Office for Official Publications of the European Communities, Luxembourg (1992).

CO-OPERATIVE PROGRAMME ON ENERGY AND DEVELOPMENT (COPED), Institutional Structures, Regulation and Performance of the Electricity Sector, de Oliviera, A. (Ed.), Office for Official Publications of the European Communities, Luxembourg (1992).

COHEN, B.C. AND COLLETTE, J.M., “Fossil Fuel Use and Sustainable Development Paths, Proc. of XXXIII International Conference, “Econometrics of Environments”, Applied Econometrics Association, Geneva (9-10 January 1992).

COMMITTEE ON ELECTRICITY (Ed.), Electricity in Economic Growth,: National Academy Press, Washington, D.C. (1986).

CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION (CIRIA), Environmental Assessment, Special Publication 96, CIRIA and Thomas Telford Services Ltd., London (1994).

COVELLO, V.T. AND MUMPOWER, J., “Risk Analysis and Risk Management: An Historical Perspective”, Risk Analysis 5 (1985).

DASGUPTA, P. AND HEAL, G., Economic Theory and Exhaustible Resources, Cambridge University Press, Cambridge, MA (1979).

DODDS, D. AND LESSER, J., Appropriate Numeric and Monetary Values for Environmental Impacts of Energy Resource Development and Use Decisions, State of Washington Interagency Task Force on Environmental Costs, Issue Paper ITF-3, Final Report, vol. II (September 1992).

DONES, R., GANTNER, U., HIRSCHBERG, S., DOKA, G. AND KNOEPFEL, I., Environmental Inventories for Future Electricity Supply Systems for Switzerland, PSI Report No. 96-07, Paul Scherrer Institute, Villigen, Switzerland (February 1996).

DONES, R., HIRSCHBERG, S. AND KNOEPFEL, I., “Greenhouse Gas Emission Inventory Based on Full Energy Chain Analysis”, in Proc. of an IAEA Workshop/Advisory Group Meeting on Full Energy Chain Assessment of Greenhouse Gas Emissions Factors of Nuclear and Other Energy Sources (Beijing, China 4-7 October 1994), IAEA-TECDOC-892, IAEA, Vienna (1996).

DONES, R., GANTNER, U. AND HIRSCHBERG, S., “Environmental Inventories for Future Electricity Supply Systems for Switzerland”, in Gheorghe, A. (Ed.), Knowledge and Decision Support Systems for Integrated Modelling in Energy Policies and Management (Special Issue of International Journal on Global Energy Issues) (1997).

DOUGLAS, M. AND WILDAVSKI, A., Risk and Culture, University of California Press, Berkeley (1982).

DUBIN, J. AND MCFADDEN, D.L., "An Econometric Analysis of Residential Electric Appliances and Consumption", Econometrica 52, pp. 345-362 (1984).

DUBIN, J., Consumer Durable Choice and the Demand for Electricity, North Holland, Amsterdam (1985).

DUBIN, J., "Will Mandatory Conservation Promote Energy Efficiency in the Selection of Household Appliance Stocks", The Energy Journal 7, pp. 99-118 (1986).

ECOTEC , Identification and Assessment of Materials Damage to Buildings and Monuments by Air Pollution, HMSO, London (1990).

ELETROBRÁS-CENTRAIS ELÉTRICAS BRASILEIRAS S A., Plano Nacional de Energia Eletrica 1993-2015, Projeto 7.A: Questao Ambiental e o Setor Elétrico (Brazilian Electricity Expansion Plan 1993-2015, Project 7.A: The Environmental Question and the Electrical Sector); Fontes de Geraçao de Energia Eletrica (Sources for Electricity Generation); Projetos Hidreletricos do Plano de Expansao (Hydroelectric Projects in the Expansion Plan); Sistemas de Transmissao (Transmission Systems), Rio de Janeiro (1993).

ELIASSON, G., The Firm and Financial Markets in the Swedish Micro-to-Macro Model: Theory, Model and Verification, Industrial Institute for Economic and Social Research, Stockholm (1985).

ENQUETE-KOMMISSION DES 11 DEUTSCHEN BUNDESTAGES, Schutz der Erdatmosphäre: Eine internationale Herausforderung, Deutscher Bundestag, Bonn (1988).

ERDMANN, G., Vorschlage zum Technischen Risikomanagement aus der Sicht der Ökonomik. Kyklos 44, 383-409 (1991).

ERDMANN, G., Energieökonomik - Theorie und Anwendungen, Verlag der Fachvereine/Teubner, Zurich/Stuttgart (1992).

ERDMANN, G., KAPPEL, R., STAUB, P. AND WIEDENMANN, R., Grenzkostenorientierte Tarifgestaltung im Elektrizitätssektor, Manuskript zuhanden des VSE, Institut für Wirtschaftsforschung, Zurich (1992).

EUROPEAN COMMISSION, Cost Effectiveness Analysis of CO_2 Reduction Options, (EC/DG-XII, JOULE Programme, Models for Energy & Environment), COHERENCE SC, Brussels (May 1991).

EUROPEAN COMMISSION (Ed.), Energy in Europe: A View to the Future, EC/DG-XVIII, Brussels (1992).

EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 1: Summary, Report No. EUR-16520-EN, EC/DG-XII, Luxembourg (1995).

EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 2: Methodology, Report No. EUR-16521-EN, EC/DG-XII, Luxembourg (1995).

EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 3: Coal and Lignite, Report No. EUR-16522-EN, EC/DG-XII, Luxembourg (1995).

EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 4: Oil & Gas, Report No. EUR-16523-EN, EC/DG-XII, Luxembourg (1995).

EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 5: Nuclear, Report No. EUR-16524-EN, EC/DG-XII, Luxembourg (1995).

EUROPEAN COMMISSION, ExternE: Externalities of Energy, vol. 6: Wind & Hydro, Report No. EUR-16525-EN, EC/DG-XII, Luxembourg (1995).

EYRE, N.J., Gaseous Emissions due to Electricity Fuel Cycles in the UK, ETSU, Harwell (March 1990).

EYRE, N.J. AND MICHAELIS, L.A., The Impact of UK Electricity, Gas and Oil Use on Global Warming, ETSU, Harwell (September 1991).

FANKHAUSER, S. AND PEARCE, D.W., The Social Costs of Greenhouse Emissions, IEA Conference on The Economics of Climate Change, OECD, Paris (June 1993).

FARMER, F.R., "Reactor Safety and Siting: A Proposed Risk Criterion", Nuclear Safety 8, 539-548 (1967).

FERGUSON, R.A.D., Environmental Costs of UK Electricity Generating Technologies, Ambient Associates, University of Northumbria (March 1994).

FISCHER, W. AND HÄCKEL, E., Internationale Energieversorgung und politische Zukunftssicherung, Das Europaische Energiesystem nach der Jahrtausendwende: Aussenpolitik, Wirtschaft, Ökologie, Oldenbourg, München (1987).

FREY, B.S., Umweltökonomie 2, erweiterte Auflage, Vanderhoek & Ruprecht, Güppingen (1985).

FRIEDRICH, R., "Life Cycle Analysis of Electricity Systems: Methods and Data Bases", paper presented in Workshop/Advisory Group Meeting on Full Energy Chain Assessment of Greenhouse Gas Emissions Factors of Nuclear and Other Energy Sources (Beijing, China (4-7 October 1994), IAEA, Vienna (1994).

FRIEDRICH, R. AND VOSS, A., "External Costs of Electricity Generation", Energy Policy pp. 114-122 (February 1993).

FRISHKNECHT, R., HOFSTETTER, P., NOEPFEL, I. AND SUTER, P., "Total Pollution including 'Grey-Pollution': Life Cycle Analysis for the Assessment of Energy Options", Proc. of 15th Congress of the World Energy Council, Madrid (1992).

FRISHKNECHT, R., HOFSTETTER, P., NOEPFEL, I. AND DONES, R., Ökoinventare für Energiesysteme - Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einvezug von Energiesystemen in Ökobilanzen für die Schweiz, 1st Ed., Paul Scherrer Institute, Zurich (1994).

FRITSCH, B., Mensch, Umwelt, Wissen: Evolutionsgeschichtliche Aspekte des Umweltproblems, 2. Auflage, Verlag der Fachvereine, Stuttgart and Zurich (1991).

FRITZSCHE, A.F., Wie sicher leben wir? Risikobeurteilung und bewältigung in unserer Gesellschaft, Verlag TUV Rheinland, Köln (1986).

FRITZSCHE, A.F. Gesundheitsrisiken von Energieversorgungssystemen, Verlag TUV Rheinland, Köln (1988).

FRITZSCHE, A.F., Wie gefährlich leben wir? Der Risikokatalog, Verlag TUV Rheinland, Köln (1992).

GIROUARD, P., Broad Economic Impacts of Nuclear Power, Proc. of 15th Congress of the World Energy Council, Madrid (1992).

GOLDEMBERG, J., REDDY, A., WILLIAMS, R. AND JOHANSSON, T., Energy for a Sustainable World, Wiley Eastern, New Delhi (1988).

GOLDEMBERG, J. AND JOHANSSON, T., Energy as an Instrument for Socio-Economic Development, United Nations Development Programme, New York (1995).

HÄFELE, W. (Ed.), Energy in a Finite World: A Global Systems Analysis, Ballinger, Cambridge MA, USA (1981).

HÄFELE, W. (Ed.), Energiesysteme im Übergang unter den Bedingungen der Zukunft, mi-Poller, Landsberg/Lechl (1990).

HIRSCHBERG, S., “Comprehensive Assessment of Energy Systems”, Magazin der ETH Zurich, Nr. 251, ETH, Zurich (November 1993).

HIRSCHBERG, S., DONES, R. AND KYPREOS, S., “Comprehensive Assessment of Energy Systems: Approach and Current Results of Swiss Activities”, in Proc. of Jahrestagung Kerntechnik 1994, Stuttgart (May 1994).

HIRSCHBERG, S. AND PARLAVANTZAS, C., “Severe Accidents in Comparative Assessments of Energy Sources: Current Issues and Actual Experience Data”, in Proc. of PSAM-II International Conf. Devoted to the Advancement of System-based Methods for the Design and Operation of Technological Systems and Processes (20-25 March 1994, San Diego), PSAM (1994).

HIRSCHBERG, S. AND CAZZOLI, E., “Contribution of Severe Accidents to External Costs of Nuclear Power”, in Proc. of European Nuclear Society Topical Meeting on PSA/PRA and Severe Accidents ‘94 (17-20 April 1994, Ljubljana), ENS (1994).

HIRSCHBERG, S. AND SUTER, P., “Methods for the Integral Assessment of Energy Related Problems”, in Proceedings of “Energietage ‘94” (10-11 November 1994, Villigen), Paul Scherrer Institute, Villigen (1995).

HIRSCHBERG, S. AND SPIEKERMAN, G., “Comparative Assessment of Severe Accident Risks Associated with Energy Generation Systems”, in Proc. of the PSAM-III International Conf. on Probabilistic Safety Assessment and Management (24-26 June 1996, Crete), PSAM (1996).

HIRSCHBERG, S., SPIEKERMAN, G. AND DONES, R., “Comparative Assessment of Severe Accident Risks in the Energy Sector”, in Proc. of 1997 Annual Meeting of the Society for Risk Analysis - Europe (15-18 June 1997, Stockholm), SRA, Stockholm (1997).

HOLDREN, J.P., Global Environmental Issues Related to Energy Supply: The Environmental Case for Increased Efficiency of Energy Use, Energy, vol. 12, No. l0/11 pp. 975-992 (1987).

HUNT, L.C., “Energy and Capital: Substitutes or Complements? Some Results for the UK Industrial Sector”, Applied Economics 16, pp. 783-789 (1984).

HUNT, L.C., “Energy and Capital: Substitutes or Complements? A Note on the Importance of Testing for Non-neutral Technical Progress”, Applied Economics 18, pp. 729-735 (1986).

INTERA ENVIRONMENTAL DIVISION, Carbon Dioxide Discharges From UK Electricity Generators and Potential Economic Impacts of Climate Change, Intera (1993).

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change: A Key Global Issue: Overview and Conclusions, WMO/UNEP, Geneva/Nairobi (1990).

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Scientific Assessment of Climate Change, The Policy Maker's Summary Report of Working Group 1 to the Intergovernmental Panel on Climate Change, WMO/UNEP, Geneva/Nairobi (1990).

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Preliminary Guidelines for Assessing Impacts of Climate Change, CGER-1005’92, Environmental Change Unit and Center for Global Environmental Research (l992).

INTERNATIONAL ATOMIC ENERGY AGENCY, Guidebook on the Introduction of Nuclear Power, Technical Reports Series No. 217, IAEA, Vienna (1982).

INTERNATIONAL ATOMIC ENERGY AGENCY, Energy and Electricity Demand Forecast for Nuclear Power Planning in Developing Countries: A reference Book, IAEA-TECDOC-470, Vienna (September 1988)

INTERNATIONAL ATOMIC ENERGY AGENCY, Electricity and the Environment: Background Papers for a Senior Expert Symposium (Helsinki, 1991), IAEA-TECDOC-624, Vienna (September 1991).

INTERNATIONAL ATOMIC ENERGY AGENCY, Renewable Energy Sources for Electricity Generation in Selected Developed Countries, IAEA-TECDOC-646, Vienna (May 1992).

INTERNATIONAL ATOMIC ENERGY AGENCY, Net Energy Analysis of Different Electricity Generation Systems, IAEA-TECDOC-753, Vienna (July 1994).

INTERNATIONAL ATOMIC ENERGY AGENCY, Comparative Health and Environmental Risks of Nuclear and Other Energy Systems, Proc. of 2nd Research Co-ordination Meeting (Athens, 13-17 Nov. 1995), IAEA-J4-RC-554.2 (Limited Distribution), Vienna (1996).

INTERNATIONAL ATOMIC ENERGY AGENCY, Health and Environmental Aspects of Nuclear Fuel Cycle Facilities, IAEA-TECDOC-918, Vienna (November 1996).

INTERNATIONAL ATOMIC ENERGY AGENCY, Thermodynamic and Economic Evaluation of Co-production Plants for Electricity and Potable Water, IAEA-TECDOC-942, Vienna (May 1997).

INTERNATIONAL ENERGY AGENCY, Energy Conservation in IEA Countries, OECD, Paris (1987).

INTERNATIONAL ENERGY AGENCY, Renewable Sources of Energy, OECD, Paris (1987).

INTERNATIONAL ENERGY AGENCY, Electricity End Use Efficiency, OECD, Paris (1989).

INTERNATIONAL ENERGY AGENCY, Energy Policies of IEA Countries, OECD, Paris (1991).

INTERNATIONAL ENERGY AGENCY, Greenhouse Gas Emissions: The Energy Dimension, OECD, Paris (1991).

INTERNATIONAL ENERGY AGENCY, Natural Gas Prospects and Policies, OECD, Paris (1991).

INTERNATIONAL ENERGY AGENCY, Energy Technologies to Reduce CO2 Emissions in Europe: Prospects, Competition, Synergy, Proc. of a Conference (11-12 April 1994, Petten, The Netherlands), OECD, Paris (1994).

INTERNATIONAL ENERGY AGENCY, Development and Deployment of Technologies to Respond to Global Climate Change Concerns, Proc. of a Conference (21-22 November 1994, Paris), OECD, Paris (1995).

INTERNATIONAL ENERGY AGENCY, New Electricity 21: Designing a Sustainable Electric System for the Twenty-first Century, Proc. of a Conference (22-24 May 1995, Paris), OECD, Paris (1996).

INTERNATIONAL ENERGY AGENCY, IEA Statistics - CO_2 Emissions from Fuel Combustion: A New Basis for Comparing Emissions of a Major Greenhouse Gas (1997 Edition: 1972-1995), OECD, Paris (1997).

JONES, J.A. AND WILLIAMS, J.A., Assessment of the Radiological Consequences of Releases from Containment Bypass Accidents from a Proposed PWR at Hinkley Point Using MARC1, NRPB M154, UK (October 1988).

KREWITT, W., MAYERHOFER, P. AND FRIEDRICH, R., "A Software Instrument Supporting Comparative Risk Assessment and the Estimation of External Costs of Energy Systems", Journal of Clean Technology and Environmental Sciences, Vol. 3, No 1, pp. 1-9 (1993).

KREWITT, W., MAYERHOFER, P., FRIEDRICH, R., GRESSMANN, A. AND DREICER, M., "External Costs as an Indicator of Different Energy Systems: A Case Study for Comparing the Nuclear and the Coal Fuel Cycle", in Proc. of PSAM-II International Conf. Devoted to the Advancement of System-based Methods for the Design and Operation of Technological Systems and Processes (20-25 March 1994, San Diego), PSAM (1994).

KYPREOS, S., "The MARKAL-MACRO Model: Links and Potential Extensions", in Proc. of IEA Energy Technologies Systems Analysis Programme: Annex V - "Seminar on Linking Technical Energy Systems Models with Macroeconomic Approaches" (Oxford, UK, 7-9 June 1993), published by ECN, Petten, The Netherlands (1993)

KYPREOS, S., "The Swiss Energy System and Greenhouse Gas Scenarios", in Kram, T. (Ed.), National Energy Options for Reducing CO_2 Emissions, vol. 2: Country Studies-A Report of the Energy Technology Systems Analysis Programme (ETSAP), Annex IV (1990-1993), Netherlands Energy Research Foundation (ECN), Report No. ECN-C-94-024 (March 1994).

KYPREOS, S., "Allocation of Carbon Tax Revenues to National and International Mitigation Options", in Carrao, C. and Haurie, A. (Eds.), Operations Research and Environmental Management, Kluwer Academic Publishers, The Netherlands (1996).

LESSER, J., Summary of State Actions to Incorporate Residual Environmental Costs Associated with Energy Resource Development, State of Washington Interagency Task Force on Environmental Costs, Issue Paper ITF-1 (February 1992).

LÜBBE, H., "Sicherheitskultur, Unsicherheitserfahrung in der modernen Gesellschaft", in: Tschirky, H. and Suter, A. (Eds.), Wieviel Sicherheit braucht der Mensch?, Verlag der Fachvereine, Zurich (1989).

MARCHETTI, C. AND NAKICENOVIC, N., The Dynamics of Energy Systems and the Logistic Substitution Model, IIASA RR-79-13, Laxenburg (1979).

MARKANDYA, A., Air Pollution and Energy Policies: The Role of Environmental Damage Estimation, Harvard Institute for International Development and University College London, London (1993).

MARTIN, J.M., "Energy and Technological Change", OECD Science and Technology Review 7 (July), OECD, Paris (1990).

MAUL, R.P. AND CLEMENT, C., Quantitative Assessments of the Environmental and Economic Impacts of Carbon Dioxide Discharges from Fossil Fuel Combustion, INTERA (March 1994).

MAYERHOFER, P., "Climate Change in the Framework of External Costs of Energy Systems, Proc. of A&WMA International Specialty Conference on Global Climate Change: Science, Policy and Mitigation Strategies (Phoenix, Arizona, USA, April 5-8, 1994).

MESSNER, S. AND STRUBEGGER, M., User's Guide to CO2DB: The IIASA CO_2 Data Bank (Version 1.0), International Institute for Applied Systems Analysis WP-91-31a, IIASA, Laxenburg, Austria (October 1991).

MESSNER, S. AND NAKICENOVIC, N., A Comparative Assessment of Different Options to Reduce CO_2 Emissions, International Institute for Applied Systems Analysis WP-92-27, IIASA, Laxenburg, Austria (March 1992).

MME-MINISTÉRIO DE MINAS E ENERGIA. ELETROBRAS-CENTRAIS Eletricas Brasileiras COMASE-Comite Coordenador das Atividades de Meio Ambiente do Setor Eletrico.(MME-Ministry of Mines and Energy. Brazil. Eletrobras-holding of the federal electrical utilities in Brazil. COMASE-Co-ordinating Committee on Environmental Activities of the Electricity Sector) Incorporatao das Variaveis Ambientais na Formulaçao do Programa Decenal de Geraçao 1994-2003 (Incorporation of the Environmental Variables into the Ten-years Expansion Programme 1994-2003) (1994).

NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM (NAPAP), The Cause and Effects of Acid Rain, Washington, D.C. (1991).

NATIONAL INDEPENDENT ENERGY PRODUCERS, Managing Externalities: Market Challenges and Solutions, NIEP, USA (October 1992).

NAVRUD, S., “Estimating Social Benefits of Environmental Improvements from Reduced Acid Depositions: A Contingent Valuation Survey”, in Studies in Environmental Science 36: Valuation Methods and Policy Making in Environmental Economics, Pages 69-102, Elevier (1989).

NERC, Critical Loads: Concept & Application. HMSO, London (1993).

NILSSON, S., “Economic Impacts of Forest Decline Caused by Air Pollutants in Europe”, in US Department of Agriculture - The Economic Impact of Air Pollution on Timber Markets, Asheville, NC, USA (1992).

NORDHAUS, W.D., “A Sketch of the Economics of the Greenhouse Effect, American Economic Review, Vol. 81, No. 2, pp.146-150 (1991).

NORWAY CENTRAL BUREAU OF STATISTICS, Natural Resources and the Environment, 91/1A, Oslo (1990).

NUCLEAR ENERGY AGENCY, Projected Costs of Generating Electricity from Power Stations for Commissioning in the Period 1995 - 2000, OECD, Paris (1992).

NUCLEAR ENERGY AGENCY, Power Generation Choices: Costs, Risks, and Externalities, Proc. of an International Symposium (23-24 September 1993, Washington, D.C., USA), OECD, Paris (1994).

NUCLEAR ENERGY AGENCY, Environmental and Ethical Aspects of Long-lived Radioactive Waste Disposal (Proc. Int. Workshop, Paris, 1-2 September 1994), OECD, Paris (1995).

NUCLEAR ENERGY AGENCY, Chernobyl - Ten Years On: Radiological and Health Aspects (An Appraisal by the NEA Committee on Radiation Protection and Public Health), OECD, Paris (1996).

NUCLEAR ENERGY AGENCY, Considerations on the Concept of Dose Constraint (Report by a Group of Experts from the NEA and the European Commission), OECD, Paris (1996).

NUCLEAR ENERGY AGENCY, Agricultural Aspects of Nuclear and/or Radiological Emergency Situations, Proc. of an OECD/NEA Workshop (Fontenay-aux-Roses, 12-14 June 1995), OECD, Paris (1997).

NUCLEAR ENERGY AGENCY, Radiation in Perspective: Applications, Risks and Protection, OECD, Paris (1997).

ONTARIO HYDRO COMPANY, Ontario Hydro’s Plan to Serve Customers’ Electricity Needs (4 Volumes: Overview; Updated Demand/Supply; Plan Report; Environmental Analysis) (1992).

ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Sustainable Development: OECD Policy Approaches for the 21st Century, Paris (1997).

OTTINGER, R.L. ET AL, Environmental Costs of Electricity, PACE University Centre for Environmental Legal Studies, Ocean Publications, New York (1990).

PEARCE, D.W., MARKANDYA, A. AND BARBIER, E.B., Blue Print for a Green Economy, Earthscan Publications Ltd., London (1989).

PEARCE, D.W., TURNER, K. AND O'RIORDAN, T., "Energy and Social Health: Integrating Quantity and Quality in Energy Planning", in Proc. of 15th Congress of the World Energy Council, Madrid (1992).

PEARCE, D.W., The Economic Value Of Externalities From Electricity Sources, University College London and University of East Anglia, The Centre of Social and Economic Research on the Global Environment (CSERGE), London (April 1993).

PLUMMER, J.L., OATMAN, E.N. AND GUPTA, P.C., Strategic Management and Planning for Electric Utilities, Prentice-Hall, Englewood Cliffs, NJ (1985).

RAIFFA, H., Decision Analysis: Introductory Lectures on Choices Under Uncertainty, Addison-Wesley, Reading, MA (1970).

RASMUSSEN, N.C., Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants: Main Report, Report No. WASH-1400, Nuclear Regulatory Commission Washington, D.C. (1975).

ROBSON, A., SHAW, T.L. AND TAYLOR, C.J.T., A Guide to the Identification and Mitigation of Environmental Issues in Construction Schemes, CIRIA Research Project 424, London (1994).

ROCARD, P. AND SMETS, H., A Socio-Economic Analysis of Controls on Land-Use Around Hazardous Installations, Geneva Papers in Insurance, Geneva (1992).

SCHÄFER, A., SCHRATTENHOLZER, L. AND MESSNER, S., Inventory of Greenhouse-Gas Mitigation Measures: Examples from the IIASA Technology Data Bank, International Institute for Applied Systems Analysis WP-92-85, IIASA, Laxenburg, Austria (November 1992).

SCHERAGA, J.D. AND LEARY, N.A., "Improving the Efficiency of Policies to Reduce CO_2 Emissions", Energy Policy (May 1992).

SCHNEEWEISS, H., Entscheidungskriterien bei Risiko, Springer Verlag, Berlin/Heidelberg/New York (1967).

SCHRAMM, G. AND WARFORD, J.J. (Ed.), Environmental Management and Economic Development, Johns Hopkins University Press, Baltimore, MD (1989).

SCHURR, S.H. AND SONENBLUM, S. (Eds.), Electricity Use, Productivity, Efficiency and Economic Growth, EPRI, Palo Alto, CA (1986).

SCHWEIZER, R. (Ed.), Naturkatastrophen und Grolsschaden 1989, Sigma der Schweizerischen Ruckversicherungs-Gesellschaft, Zurich (1990).

SHAVELL, S., "Risk Sharing and Incentives in the Principal Agent Relationship", Bell Journal of Economics 10, pp. 55-73 (1979).

SIEBERT, H., Ökonomische Theorie natürlicher Resourcen, Mohr, Tübingen (1983).

SIMONIS, U.E. (Ed.), Präventive Umweltpolitik, Campus, Frankfurt (1988).

SIMONIS, U.E., Ökonomie und Ökologie: Auswege aus einem Konflikt, 5. ergänzte Auflage, C.F. Muller, Karlsruhe (1988).

SIOSHANSI, F.P., “The Myths and Facts of Energy Efficiency: Survey of Implementation Issues”, Energy Policy 19, pp. 231-243 (1991).

SMITH, A., Analysis of Energy Policy and Greenhouse Gas Proposals: GEMINI-UK Model, Report 2430, Decision Focus Inc., Palo Alto, CA (1993).

STAM, E., A Review of the Institutional Arrangements in the Electricity Supply Industry, ELECTRA (CIGRE) No. 163 (December 1995).

STARR, C., “Risk Management, Assessment, and Acceptability”, Risk Analysis 5, pp. 97-l02 (1985).

STARR, C., “Functional Perspective on Risk Analysis in Nuclear Power”, in Probabilistic Safely Assessment and Risk Management (vol. I), TUV Rheinland, Köln (1987).

STOKEY, E. AND ZECKHAUSER, R., A Primer for Policy Analysis, Norton, New York (1978).

TURVEY, R. AND ANDERSON, D., Electricity Economics, Johns Hopkins University Press, Baltimore, MD (1977).

UCHIYAMA, Y., “Overview of FENCH-GHG Analysis: Case Study in Japan”, in Proc. of an IAEA Workshop/Advisory Group Meeting on Full Energy Chain Assessment of Greenhouse Gas Emissions Factors of Nuclear and Other Energy Sources (Beijing, China 4-7 October 1994), IAEA-TECDOC-892, IAEA, Vienna (1996).

UCHIYAMA, Y., “Validity of FENCH-GHG study: Methodologies and Data Bases”, in Proc. of an IAEA Workshop/Advisory Group Meeting on Full Energy Chain Assessment of Greenhouse Gas Emissions Factors of Nuclear and Other Energy Sources (Beijing, China 4-7 October 1994), IAEA-TECDOC-892, IAEA, Vienna (1996).

UNITED KINGDOM DEPARTMENT OF THE ENVIRONMENT, This Common Inheritance, Britain's Environmental Strategy, HMSO, London (1990).

UNITED KINGDOM DEPARTMENT OF TRADE AND INDUSTRY, Energy Related Carbon Emissions in Possible Future Scenarios for the UK, Energy Paper 59, HMSO, London (1992).

UNITED KINGDOM PARLIAMENTARY OFFICE OF SCIENCE AND TECHNOLOGY, Costing the Environmental Impacts of Electricity Generation, London (1992).

UNITED STATES DEPARTMENT OF ENERGY, ENERGY INFORMATION ADMINISTRATION, The Changing Structure of the Electricity Power Industry: An Update, DOE/EIA-0562(96), Washington, D.C. (December 1996).

VILLELA, N. P., Environmental Issues of the Serra da Mesa hydroelectric Power Plant, World Energy Council Studies Committee Program, Project 4 of Environment Work Group C, Local and Regional Related Environmental Issues, Furnas Centrais Elétricas SA, Rio de Janeiro (1994).

VILLELA, N.P., The Brazilian Experience in Environmental Impact Reduction in Hydroelectric Power Plants under Construction and Operation, Itaipu-Three Gorges Seminar (Yichang, China, November 1994).

VIREN, M., “Estimating the Output Effects of Energy Price and Real Interest Rate Shocks: A Cross Country Study”, Schweizerische Zeitschrift für Volkswirtschaft und Statistik 122, pp. 627-639 (1986).

VON WINTERFELDT, D. AND EDWARDS, W., Decision Analysis and Behavioral Research, Cambridge University Press, Cambridge, UK (1986).

WESTOBY, R., Long Run Price Elasticities for Energy: An Overview of Existing Energy Models, Department of Political Economy, Aberdeen (1981).

WHEELER, G. AND HEWISON, R.C., The External Costs of Accidents at a UK PWR, INTERA (April 1994).

WOOLF, T., "Its Time to Account for the Environmental Costs of Energy Sources", Journal of Environmental Management (1993).

WORLD ENERGY COUNCIL AND INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, Global Energy Perspectives to 2050 and Beyond, WEC, London (1995).

WORLD ENERGY COUNCIL, Energy for Tomorrow's World, Kogan Page (1993).

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