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Incorporating Environmental Concerns into Power Sector Decisionmaking

A Case Study of Sri Lanka

Peter Meier and Mohan Munasinghe

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CONTENTS

ABBREVIATIONS

ADAB	Australian Development Assistance Bureau
AFBC	Atmospheric fluidized bed combustion
AIC	Average incremental cost
ADB	Asian Development Bank
CBA	Cost-benefit analysis
CEA	Central Environment Authority
CEB	Ceylon Electricity Board
DSM	Demand side management
EA	Environmental assessment
EIS	Environmental impact statement
EPRI	Electric Power Research Institute
ESP	Electrostatic precipitator
FBC	Fluidized bed combustion
FGD	Flue gas desulfurization
GEF	Global Environment Facility
GTZ	Gesellschaft fur Technische Zusammenarbeit (German Agency for Technical Assistance)
IRP	Integrated resource planning
IRR	Internal rate of return
LP	Linear programming
LECO	Lanka Electricity Company
ODA	Overseas Development Administration (of the United Kingdom)
MEIP	Metropolitan Environmental Improvement Program
NARA	National Aquatic Resources Agency
NPV	Net present value
NBRO	National Building Research Organization
PFBC	Pressurized fluidized bed combustion
SLF	System load factor
T&D	Transmission and distribution
USAID	United States Agency for International Development

FOREWORD

The decade of the 1980s witnessed a fundamental change in the way governments and development agencies think about environment and development. The two are no longer regarded as mutually exclusive. It is now recognized that a healthy environment is essential to sustainable development and a healthy economy. Moreover, economists and planners are beginning to recognize that economic development that erodes natural capital is often not successful. In fact, development strategies and programs that do not take into adequate account of the state of critical resources -- forests, soils, grasslands, freshwater, coastal areas, and fisheries -- may degrade the resource base upon which future growth is dependent.

Since its creation, the Vice Presidency for Environmentally Sustainable Development (ESD) has placed the highest priority on the analysis of these important issues. Within ESD, the Environment Department's work, in particular, has focussed on the links between environment and development and the implications of these links for development policy in general. The objective of the Environment Paper Series is to make the results of our work available to the general public.

Increasing environmental awareness and concerns over sustainability have broadened the range of issues that need to be examined in the assessment of the potential impacts of proposed projects and programs. Three different concepts of sustainable development may be identified; based on economic, ecological, and sociocultural criteria. Reconciling these concepts and integrating them into operations will be a formidable task, which is only now getting underway. In the meantime, those making decisions have to find ways of introducing such concerns into their analysis in a practical way.

Nowhere is the incorporation of environmental externalities into decisionmaking more important than in the power sector where environmental concerns -- ranging from greenhouse gas emissions of fossil fueled power plants to the impacts of inundation at hydro plants -- have posed increasingly difficult constraints to project implementation. Although great progress has been made in improving environmental assessment procedures at the project level, it has become increasingly evident that these must be complemented with procedures to incorporate environmental concerns at the long-range planning and siting stage as well.

Sustainable energy development cannot be achieved by project level mitigation measures alone but require that environmental concerns be integrated into decisions about the appropriate mix of supply and demand side measures, the mix of generation (and the role of renewable energy sources in particular), and the policy environment in which sector development occurs. For example, a pricing policy that provides the right signals to consumers to use electricity more efficiently is as important to sustainable development as plant level mitigation measures to minimize particulate emissions, or appropriate policies for resettlement at hydro plants.

This paper examines ways to achieve such integration of environmental concerns at an early stage of sector planning, using the specific example of Sri Lanka. It seeks to help analysts, practitioners, and policymakers in the field by developing practical procedures to assist decisionmaking. It does this not just by extending conventional cost-benefit analysis but by making use of other methods such as multicriteria decision analysis.

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and Director, Environment Department.

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ABSTRACT

This case study of Sri Lanka seeks to demonstrate how environmental concerns can be incorporated into the planning stage of power sector development. The techniques and procedures are designed to complement existing approaches to environmental assessment that are now a routine part of project development.

The centerpiece of this study is a methodology for incorporating environmental considerations into power sector planning. Although the application of recently developed valuation techniques permits some impacts to be folded into a conventional benefit-cost analysis, for many of the most important power sector impacts this becomes very difficult. This has two reasons. The first is the nature of the impacts themselves -- the health effects of pollutants from coal fired generating stations, the potential loss of biodiversity associated with large scale hydro reservoirs, the impacts of greenhouse gas emissions -- all are exceptionally difficult to value. Indeed, attempts to do so would very likely focus attention on the validity of the validation techniques themselves, rather than the policy trade-offs that must be made.

The second reason concerns the scale of analysis. The techniques for economic valuation of environmental externalities are usually most appropriate to the project level: for example, the use of the contingent valuation method is much more valid where respondents can be asked specific questions about specific impacts of a specific project to which they can relate. However, this may be very difficult to apply in the context of long range sector planning where one is dealing with a potentially large number of technology, site and mitigation options.

It is in these kinds of situations where the techniques of multi-attribute analysis may be applied. These techniques first gained prominence as an evaluation technique in the 1970s, when the intangible environmental externalities lying outside conventional cost-benefit analysis methodologies were increasingly recognized. It also met one objective of modern decisionmakers, who preferred to be presented with a range of feasible alternatives -- as opposed to one "best" solution. And it allows for the appraisal of alternatives with differing objectives and varied costs and benefits, which are often assessed in differing units of measurement.

The problem of comparing disparate types of impacts is particularly acute in the case of Sri Lanka, where the main generation options -- hydro and baseload thermal -- have impacts that are totally different in character. Moreover, mitigation of power sector impacts must also be seen in the broader context of optimal resource allocation: for example the cost-effectiveness of stringent environmental regulation remotely located coal plants with tall stacks must be put into the context of measures to reduce automobile emissions in densely populated urban areas. Indeed, one of the conclusions of this case study is that if coal-fired baseload plants are eliminated from the supply mix-- whether for reasons of seeking to reduce greenhouse gas emissions, or for perceived problems of air and solid waste emissions -- the actual environmental impacts of the diesels that would replace them may be much greater absent complementary policies to regulate siting and fuel quality.

Even without the additional complication introduced by the environmental objective, power sector planning is undergoing some fundamental changes. First, much greater attention is being paid to a more balanced treatment of supply and demand resources --

known in the United States as integrated resource planning. Second, much greater attention is being paid to the robustness of investment programs to the significant uncertainties that affect the sector. Thus, rather than seeking a single "least cost" plan, that may be optimal only over a rather narrow band of assumptions, planners are making increasing use of decision analysis techniques to deal with risk and uncertainty.

In this case study, therefore, the methodology is applied to the assessment of a wide range of policy options, including representative demand-side management measures, renewable energy options (such as wind power), and clean coal technologies (which promise inherently better environmental performance than conventional combustion technologies fitted with "end-of-pipe" treatment systems).

1. BACKGROUND

The importance of sustainable development was highlighted at the 1992 Earth Summit in Rio de Janeiro. Sustainable development has three key elements -- economic, environmental, and social (Munasinghe, 1993). While the link between energy and economic growth has been accepted for many decades, in recent years the environmental and social impacts of energy development have become an increasingly important topic of public debate in both the developed and the developing countries.[1] In the developing countries, this debate is part of a broader emerging concern over strategies for sustainable development,[2] as donor agencies[3] and the international financial institutions have become increasingly concerned about implementing new policies that respond more effectively to environmental and social goals.[4]

In this general climate of increasing scrutiny into the environmental implications of the development process, the power sector has received particular attention, a consequence of the significant potential environmental impacts associated with the sector. Indeed, historically, many of the most celebrated instances of unanticipated environmental consequences in developing countries have occurred at major power project sites -- such as at the Akosombo Dam in Ghana, and the Aswan Dam in Egypt. But even though it is quite unlikely that one would today encounter unanticipated impacts on the scale encountered at such past projects (given the procedures now in place), there is general agreement that the most pressing need is to incorporate environmental concerns proactively into investment planning and decision-making rather than simply reacting to environmental problems after they occur.

One approach is to value environmental costs and benefits in economic terms, and to incorporate them into conventional benefit cost analysis that is the basis for present planning procedures. Over the past few years economic valuation methods have become increasingly used in a variety of applications. But while some impacts encountered at power facilities can be so treated, there are many for which the application of the techniques available poses great difficulty. The major reason is the nature of the impacts themselves -- the health effects of pollutants from coal fired generating stations, the potential loss of biodiversity associated with large scale hydro reservoirs, the impacts of greenhouse gas emissions -- all are exceptionally difficult to value. Indeed, attempts to do so would very likely focus attention on the validity of the valuation techniques themselves, rather than on the policy trade-offs that must be made.

It is in such situations that the techniques of multi-attribute analysis may be applied. These techniques first gained prominence in the 1970s, when the intangible environmental externalities lying outside conventional cost-benefit methodologies were increasingly recognized. It also met a key objective of modern decisionmakers -- the desire to be presented with a range of feasible alternatives as opposed to one "best" solution. It allows for the appraisal of alternatives with differing objectives and varied costs and benefits, which are often assessed in differing units of measurement.

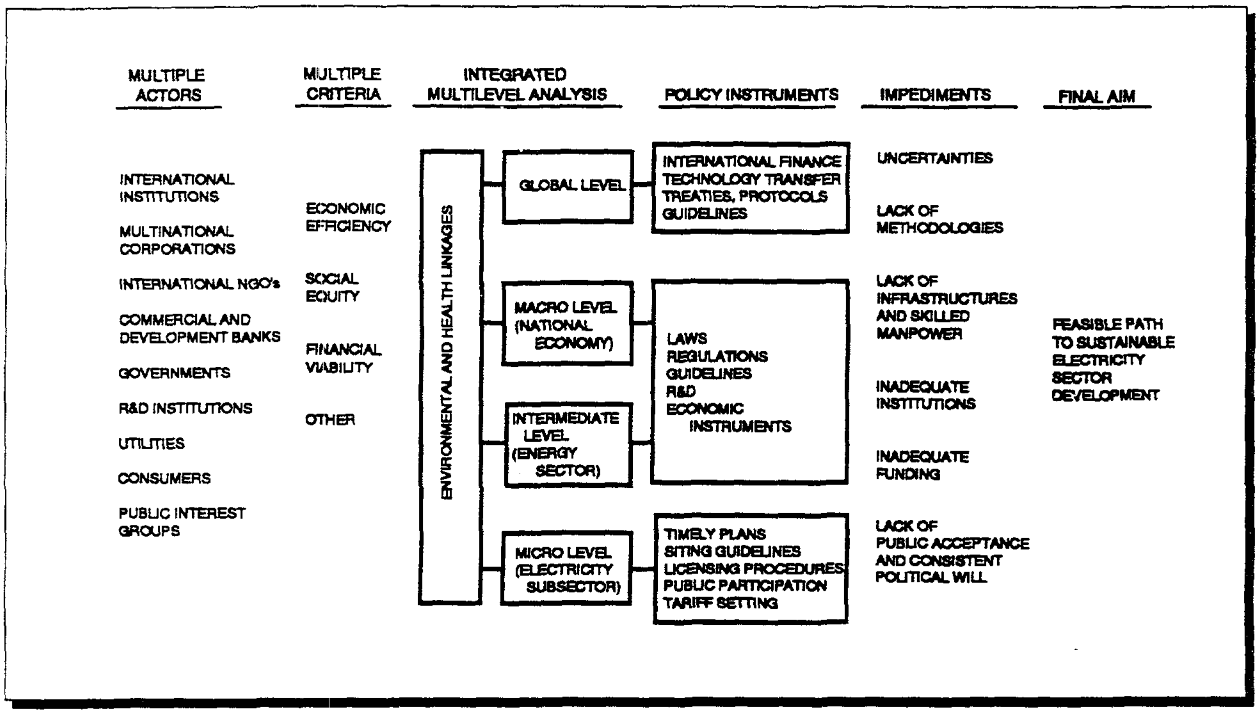


Figure 1.1: A Comprehensive Framework for energy decision-making

Adapted from: Munasinghe *et al.* (1991)

This study illustrates how both economic valuation and multiattribute approaches might be used to better incorporate environmental concerns into power sector planning, using Sri Lanka as a case study. Sri Lanka presently depends largely on hydro power for electricity generation, but over the next decade there seems little choice but to begin building large coal or oil fired stations, or to build hydro plants whose economics and environmental impacts are increasingly unfavorable. In addition, there are a wide range of other options, such as wind power, increasing use of demand side management, and system efficiency improvements, among others, that complicate the planning process.

Power and energy decision-making in the national context

The broad rationale underlying all national level planning and policy-making is the need to ensure the best use of scarce resources, in order to further socio-economic development efforts and improve the quality of life of citizens. Power and energy planning must also be part of, and closely integrated with overall economic planning and policy analysis, to meet many specific, inter-related and frequently conflicting national objectives. Specific goals might include: (a) ensuring economic efficiency in the supply and use of all forms of energy, to maximize growth -- other efficiency related objectives are energy conservation and elimination of wasteful consumption, and saving scarce foreign exchange; (b) raising sufficient revenues from energy sales to finance sector development; (c) meeting the basic energy needs of the poor, and income redistribution; (d) diversifying supply, reducing dependence on foreign sources, and meeting national security requirements; (e) contributing to development of special regions (particularly rural or remote areas), and priority sectors of the economy; (f) price stability; (g) preserving the environment; and so on.

Successful planning and implementation of national energy programs must explicitly take account of the role of the energy sector in economic development vis-a-vis those of the other parts of the economy. This will require an integrated approach to help decisionmakers formulate policies and provide market signals and information to economic agents that encourage efficient energy production and use. Summarized in Figure 1.1 is an integrated approach to decision-making which emphasizes a hierarchical conceptual framework for integrated national energy planning and policy-making (INEP) that can be implemented through a set of energy supply and demand management policies.[5]

The core of the INEP framework is the integrated multilevel analysis shown in the middle column. Although INEP is primarily country-focused, at the global level it is recognized that there are transnational energy-environmental issues. Thus individual countries are embedded in an international matrix, and economic and environmental conditions at this global level will impose exogenous inputs or constraints on decisionmakers within countries. The next hierarchical level in Figure 1.1 focuses on the multisectoral national economy, of which the energy sector is a part. This suggests that energy planning requires analysis of the links between the energy sector and the rest of the economy. Such links include the energy needs of user sectors (e.g., industry, transport and agriculture), input requirements of the energy sector, and impact on the economy of policies concerning energy prices and availability. The intermediate level of INEP treats the energy sector as a separate entity composed of subsectors such as electricity, petroleum products and so on. This permits detailed analysis, with special emphasis on interactions among the different energy subsectors, substitution possibilities, and the resolution of any resulting policy conflicts. The most disaggregate and lowest hierarchical level pertains to analysis within each of the energy subsectors. At this level most of the detailed energy resource evaluation, planning and implementation of projects is carried out by line institutions (both public and private).

In practice, the various levels of INEP merge and overlap considerably, requiring that (inter-) sectoral linkages should be carefully examined. Energy-environmental interactions (represented by the vertical bar) tend to cut across all levels and need to be incorporated into the analysis as far as possible. Such interactions also provide important paths for incorporating environmental considerations into national energy policies.

INEP facilitates policy-making and does not imply rigid centralized planning. Thus, such a process should result in the development of a flexible and constantly updated energy strategy designed to meet national goals. This national energy strategy (of which the investment program and pricing policy are important elements) may be implemented through energy supply and demand management policies and programs that make effective use of decentralized market forces and incentives.

Consequently, INEP implies improvements in overall economic efficiency through better energy management. As shown in Figure 1.1, a variety of policy instruments are available to decisionmakers for instituting sound energy management. The figure also indicates the most important impediments that limit effective policy formulation and implementation.

While recognizing the need for the broader decision-making framework, in this study we will focus on power system planning -- in particular, how environmental concerns may be incorporated better into the decision-making process at this specific level of the planning hierarchy, with an emphasis on improving the tools for environmental-energy analysis and policy formulation in the power sector. However, there is a clear implication that this is only one prerequisite for improved decision-making and policy implementation. The latter will require effective functioning of all parts of the comprehensive framework shown in Figure 1.1.

Power sector planning

In the past, the principal planning objective for the development of the power sector has been to deliver the anticipated need for electrical energy at "least cost". Indeed, largely at the insistence of the World Bank and other international financial institutions, developing countries have had to demonstrate that facilities proposed for financing are in the "least cost" plan. In practice this has meant the application of sophisticated capacity expansion optimization models -- such as the WASP model which is very widely used in developing countries[6] -- whose objective function is the minimization of the present value of system expansion costs over some planning horizon and for some given level of system reliability.

Yet in the complex regulatory environment of the industrialized countries, few utilities use the results of mathematical optimization models to develop their capacity expansion plans. The most common approach is to develop a small number of discrete options, with revenue requirements and environmental impacts derived in some detail as part of the necessary regulatory submissions. Moreover, "least cost" planning in countries such as the United States has come to encompass a much broader perspective than the traditional stress on minimizing the costs of supply expansion for some exogenously specified level of demand, since the demand itself is subject to modification by so-called demand side management approaches[7]. Indeed, over the past few years a number of U.S. state regulatory commissions have expanded the operational definition of "least cost" planning even further by introducing specific techniques for including the costs of environmental externalities as well.

In fact the problems of an excessive reliance on supply side optimization models as a basis for planning in the developing countries has become broadly recognized by many lately, including voices within the World Bank itself.[8] Perhaps the most important objection to the use of the traditional models such as WASP is the difficulty with which they deal with the huge uncertainties currently faced by the sector, ranging from unpredictable prices of imported fuels to the impacts of construction cost overruns and droughts. Thus the so-called "least cost" plan may in fact be optimal only for the particular set of external circumstances assumed, and may deviate from optimality for most other combinations of external factors.

In the traditional approach to power sector planning, environmental considerations have generally been deferred to at least the siting stage of individual projects. In other words, earlier decisions about the generation mix, and the basic technology choices, have been made entirely on the grounds of direct costs; although in the case of hydro projects easily quantified mitigation costs -- such as the cost of resettlement, or the opportunity costs of foregone production from inundated land -- are now routinely incorporated into economic analysis.[9]

Attempts to quantify environmental factors at the siting stage -- efforts that are quite common in the United States and growing in developing countries-- have tended to rely on some very ambiguous ranking and weighting schemes, with an ubiquitous reliance on "judgement and experience of siting experts". As we shall see below (in Chapter 7), it is quite unclear whether such approaches have in fact improved the quality of siting decisions.

A detailed examination of environmental issues has heretofore tended to be deferred to the project level environmental assessment (EA). Quantification at this level of analysis has generally required the application of mathematical models of the fate of pollutants in the environment -- such as atmospheric dispersion models for air pollutants, and thermal plume models for predicting ambient water temperature increases from cooling water discharges. However, the thrust of such modelling studies is to demonstrate compliance with ambient standards: if these are not met, mitigation options are explored to bring the facility into compliance. An analysis of actual impacts -- say in the case of air quality, an estimation of the health risks associated with pollution exposure -- is rarely part of such assessments.

In general not much detail is presented on the impacts at alternative sites, whatever may be the regulatory requirement that alternatives to the proposed action need to be examined. More often than not, in an EA of several hundred pages, there is but a few pages of discussion about alternative sites: and such material as is provided is often in the nature of undocumented (and usually unquantified) assertion. Very rarely in a project level EA is there any discussion of alternative generating mixes, or of

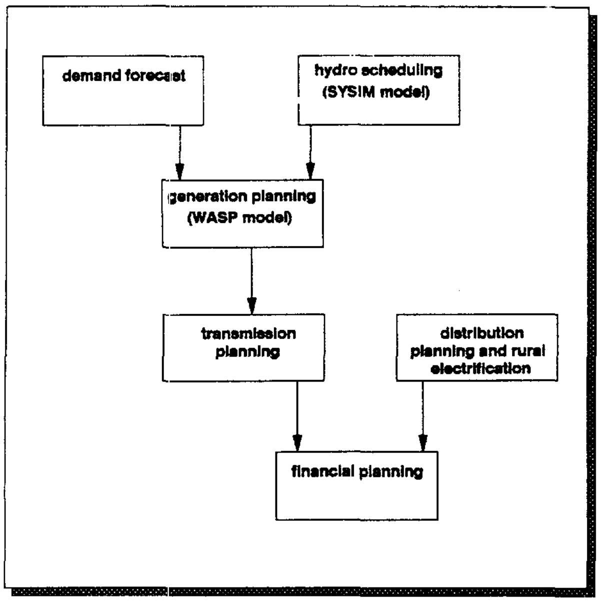


Figure 1.2: The power planning process in Sri Lanka

general energy and pricing policy that might have lessened the need for the plant in question.

The planning process in Sri Lanka

This general characterization of the planning process applies almost perfectly to Sri Lanka (see Figure 1.2). The annual planning cycle begins with load forecasts, which are used in turn by the Generation Planning Branch as a basis for their generation plan, for which the WASP-III model is currently used. Hydro scheduling is done with the SYSIM model, which was developed as part of the Electricity Masterplan sponsored by the German assistance agency GTZ.[10]

Both the Masterplan system expansion studies, as well as the present CEB Generation plan, have in the past restricted their consideration of environmental issues to a few calculations of residuals: yet the usefulness of such calculations and their graphical portrayals could be improved and may have very little to do with the actual environmental impacts that might be expected. For example, in Figure 1.3, the simple horizontal "stacking" of SO_2, NO_x and ash emissions provides a visual implication that tons of these very distinct pollutants could be arithmetically added together to yield some form of aggregate impact.

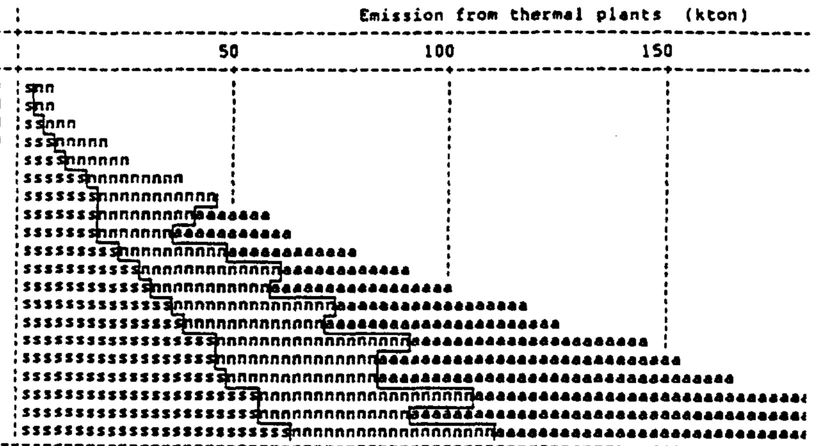
As will be discussed in more detail in Chapter 3, the approach followed in the early 1980's with respect to the siting of new coal plants again followed very much the traditional pattern. Environmental issues were addressed in detail only as part of the project level EA, once the basic siting decision -- for a coal-burning baseload station at Trincomalee on the east coast -- had already been made. The subsequent decision to examine a site on the south coast, followed by yet another political decision to drop further consideration of that site, illustrates the largely ad hoc nature of how environmental considerations were being addressed. More recently the Kukule hydro-electric project has come to the forefront of public debate and controversy; again there is the danger of increasing public perception increasing that feasibility study which is currently underway will inevitably lead to its construction irrespective of the environmental findings.

The need for an earlier and more systematic approach to analyzing the environmental aspects of power system alternatives in Sri Lanka is quite clear. The *ad hoc* procedures of the past, in which major projects are examined one at a time, and rejected one at a time, will create substantial problems in the future unless a more pro-active approach is taken. We hope that this case study will make a small contribution to starting the necessary reforms.

Incorporating environmental concerns into the planning stage

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.[11] This is reflected in the recent experience of the industrialized countries as well. For example, in the United States, despite increasing pressures to do so, many state regulatory commissions have yet to adopt formal procedures for including environmental externalities. Most of those that have done so,

Year	Type of emission		
	SO2	NOx	Ash
1991	3	5	0
1992	3	5	0
1993	5	9	0
1994	8	12	0
1995	11	17	0
1996	15	24	0
1997	19	29	0
1998	19	23	14
1999	19	18	26
2000	24	26	26
2001	29	33	27
2002	30	28	41
2003	37	39	41
2004	37	33	55
2005	45	45	55
2006	45	38	69
2007	48	36	82
2008	57	50	82
2009	55	36	107
2010	64	49	109
Total	573	555	734



s Type of emission SO2
n Type of emission NOx
a Type of emission Ash

Figure 1.3: Masterplan portrayal of residuals

Source: GTZ Masterplan, Volume A-6, System Expansion Studies.

have adopted somewhat crude expedients that seem little related to rigorous cost-benefit analysis.[12]

A second feature of the emerging literature on the subject of how to incorporate environmental considerations into energy and power sector planning in developing countries, is the perception that somehow the analytical approaches that should be used are "different" than those used in the developed countries -- presumably because public sector investment plays a much larger role in many developing countries, and, in the case of electric utilities, because of the substantial differences in the ownership and regulatory frameworks.[13] That however is a matter of the effectiveness of the different policy instruments available, and has nothing to do with the analytical methodology that enables one to quantify the linkages between the configuration of the power system, economic costs, and environmental quality.[14] Whether, for example, investments are made by state-owned electric utilities (as in developing countries), or by privately owned utilities under regulatory supervision (as in the United States) does not alter the linkage, say, between a requirement for flue gas desulfurization systems and ambient air quality. It affects only how a policy that would require such systems might be implemented[15].

In fact 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 formalize the process into operational models. The recent review of models and the literature by Markandya[16], despite its stated focus on power systems planning, found that most of the emphasis to date has been on modifying much broader energy systems models to deal with environmental constraints or objectives.[17] The only model that can be regarded as a power systems model for which any attempt has been made to incorporate environmental considerations, and which has been used extensively in developing countries, is the WASP model for which a so-called IMPACTS module was developed a few years ago by Argonne National Laboratory.[18] However, this module calculates only the quantity of pollutants emitted (or "residuals"), together with cost estimates for any pollution control devices. It does not deal with impacts *per se*.[19]

Given this dearth of methodologies, it is hardly surprising that most of the attention to date has been given to improving environmental assessment procedures at the project level. Thus the World Bank, for example, now has extensive new procedures in place to ensure inclusion of environmental concerns in the project cycle.

Nevertheless, even if done well, there are inherent limitations to the degree to which EA and cost-benefit analysis (CBA) at the project level can address the most important environmental issues.[20] The project level EA deals well with local, site specific questions, and options for project level mitigation (such as resettlement questions at dams, loss of wildlife habitat, or local socio-economic impacts associated with construction). However, the project level EA deals less effectively with regional (e.g. downstream water quality impacts), national (e.g. acid rain) and global scale (e.g. greenhouse gas) issues. These can really be addressed only at a much broader scale than that of the single project, namely at the scale of the system plan. At this level of the planning process, the fundamental question is not whether the impact of any single project is environmentally acceptable, but what the relative environmental costs and benefits are of alternative power sector development strategies.

Indeed, there are widespread perceptions that project level EAs are nothing more than ex-post justifications of decisions already made.[21] In Sri Lanka, the first full-scale EA for a power project was prepared for the opposed Trincomalee coal fired power plant;[22] and many of the public comments reflected just this perception.[23]

While it is perhaps easy to dismiss such fears as mere rhetoric, in fact very few EAs for power projects have concluded that the project should not go forward.[24] It is probably fair to assert that the twenty years of experience with EAs has shown that while they have succeeded in forcing project developers to become more sensitive to environmental issues, and in ensuring that mitigation options are fully integrated into the project design, they have proven to be inadequate as a tool for ensuring that environmental considerations are incorporated into the planning decision process itself.[25]

In response to such problems, this study seeks to explore alternative approaches to quantifying and valuing environmental impacts at the planning stage in the power sector. The express objective of this effort is to develop methodologies that can be implemented in practical ways, and whose potential impact on decision rules is clearly demonstrable. In particular we examine the practicality of using multi-attribute decision analysis in a developing country setting when economic valuation of environmental impacts is difficult. We seek to demonstrate the usefulness of such techniques as a way of better incorporating environmental goals into power sector decision-making at the investment planning stage. We believe the case study approach to be particularly appropriate to developing countries, insofar as there already exists a substantial theoretical literature on the subject, and a great deal of experience in the developed countries.

Nevertheless, the difficulties of such a task are worth stating clearly at the outset. Even in the industrialized countries, where the information base is much better than that which is encountered in most developing countries, the difficulties in determining operationally useful procedures to incorporate environmental externalities into energy decision-making have been substantial, and the methods used are in some cases quite crude. One recent review of the state of the art concluded that "determining the environmental externality cost of electric utility operations is a monumental task, and it is clear that a great deal more work needs to be done."[26]

The outline of the study

We begin, in Chapter 2, with an overview of the proposed methodology. The remaining chapters of the report are then organized in such a way that each covers one of the important elements of the approach.

Thus, in Chapter 3, we continue with a discussion of the development options for the power sector in Sri Lanka. The range of choices include technology, fuel supply, and siting options, as well as the major systemwide mitigation options -- such as a potential requirement for flue gas desulfurization systems at coal burning power plants. Moreover, we examine not merely supply side capacity expansion, but also options for demand side management and improving overall system efficiency -- such as reducing transmission and distribution (T&D) losses.

The relevant environmental issues associated with the power sector that are of importance to national policy-makers in Sri Lanka are introduced in Chapter 4.

In Chapter 5 we then tackle the problems of economic valuation of environmental impacts. After a review of the theoretical framework and valuation techniques, we attempt an analysis for Sri Lanka using damage cost estimates drawn from the literature. The results point out the need for in-country valuation studies that go beyond the scope and resources of the present study, and also highlight the advantages of using multi-attribute methods in situations where valuation approaches are subject to great uncertainties or controversy (as in the case of valuation of human life).

Multi-attribute techniques are presented in Chapter 6, with the emphasis on how to define criteria for narrowing down the often very large set of candidate options to some subset that merits further examination. This is followed, in Chapter 7, by a brief review of some of the applications of such methods in the literature, and in Sri Lanka itself.

In Chapter 8 we define the environmental attributes to be used. To capture the potential impact on global warming, CO_2 emissions were defined as the appropriate proxy. To be sure, the relationship between global CO_2 concentrations and the actual physical impacts that may follow, such as sea level rise or changes in monsoonal rainfall patterns are still poorly understood, and in any event unlikely to be captured by simple linear correlations. However, since Sri Lanka's contribution to worldwide emissions will remain extremely small, the assumption of linearity of impacts (relative to global CO_2 emissions) is not unreasonable.

To capture health impacts, we used the population-weighted increment in fine particulates and NO_x attributable to each source. To this end we applied a simple Gaussian plume model to all of the major sites, calculated incremental ambient concentrations for 1km square cells to within a 20km radius, and multiplied by the population in each cell.

To capture other potential air pollution impacts, such as acid rain, we used SO_2 and NO_x emissions. As an illustrative social impact, we used the creation of labor opportunities. Employment creation is an important objective of national policy, and in Sri Lanka there has occurred frequent discussion of the need for employment creation in the south where youth unemployment rates are especially high. It should be noted that what is captured in this attribute is the separate and purely political objective of employment creation, and is to be distinguished from strictly economic benefits that would be captured by the use of shadow wage rates (to reflect high unemployment in the construction sector). All of these impacts were appropriately discounted and expressed as a present value. Finally, to capture the potential biodiversity impacts, we derived a probabilistic index based on information likely to be available at the project planning stage.

The multicriteria analysis is developed in Chapter 9. With options and attribute definitions in hand, we generate the multidimensional trade-off space. Using the ENVIROPLAN model, the attribute values for each of the environmental attributes, and the cost attribute (for which average incremental cost over a 20-year planning horizon was used) were calculated for every option, with results displayed as a series of two-dimensional trade-off curves. In a final step, the list of candidate plans for further study was then derived by examining dominance relationships among all criteria simultaneously.

The policy implications and conclusions of the study are presented in Chapter 10. First, the results of the case study indicate that those impacts for which valuation techniques are relatively straight forward and well-established -- such as valuing the opportunity costs of lost production from inundated land, or estimating the benefits of establishing fisheries in a reservoir -- tend to be quite small in comparison to overall system costs, and their inclusion into the benefit-cost analysis does not materially change results.

Second, even in the case where explicit valuation may be difficult, such as in the case of mortality and morbidity effects of air pollution, implicit valuation based on analysis of the trade-off curve can provide important guidance to decision makers. For example, the study determined that the value of human life necessary to justify flue gas desulfurization at potential sites for coal fired-power plants was on the order of $1.5million. This is at least one (if not two) orders of magnitude greater than the value necessary to justify the installation of modern diagnostic equipment at the regional hospitals.

Third, the case study indicated that certain options were in fact clearly inferior, or clearly superior, to all other options when one examines all impacts simultaneously. For example, the high dam version of the Kukule hydro project can be safely excluded from all further consideration as a result of poor performance on all attribute scales (e.g. biodiversity as well as economic). On the other hand, implementation of certain demand side management measures dominates all other options.

Fourth, the results indicate that it is possible to derive attribute scales that can be useful proxies for impacts that may be difficult to value. For example, use of the population-weighted incremental ambient air pollution scale as a proxy for health impacts permitted a number of important conclusions that are independent of the specific economic value assigned to health effects. For example, the study clearly demonstrated that if indeed the health effects of pollutants associated with fossil fuel combustion (particularly fine particulates and NO_x) are to be considered, then the most effective strategy for reducing the overall population dose is to install tighter pollution controls (for instance to require the use of low sulfur fuels) at oil-burning power plants located in or near urban areas, rather than installing FGD systems at the more remote sites suitable for coal-burning power plants.

The study also derives several recommendations for the Ceylon Electricity Board (CEB) for improving the way in which it deals with environmental issues. These include:

1. The need to incorporate the easily quantified secondary costs of hydro facilities -- such as the costs of relocation and resettlement -- into the capital costs used in generation planning studies;

2. The need for independent peer review of environmental assessments (in a similar manner in which this is being done for technical feasibility studies).

3. A set of recommended priority activities for the Environmental Cell that is to be established in the CEB under the National Environmental Action Plan.

Finally, with respect to the practical implications for planning, we draw several specific recommendations on priority options, that ranked high on environmental as well as the economic attributes. These include:

1. The need to systematically examine demand side management options, especially fluorescent lighting (for which the collection of end-use load data is the essential prerequisite).

2. The need to examine whether the present transmission & distribution loss reduction target ought to be further reduced.

3. The need to examine the possibilities of pressurized fluidized bed combustion (PFBC) technology for coal power.

The report concludes with an annex that summarizes the highlights of the computer model used to generate the results of this study. A separate report contains a more detailed technical documentation.[27]

Notes

[1] For a good general discussion of the major issues, see e.g. *Senior Expert Symposium on Electricity and the Environment: Key Issues Papers*, International Atomic Energy Agency, Vienna, 1991.

[2] See e.g. *Asian Development Bank, Economic Policies for Sustainable Development*, Manila, 1990.

[3] However, it would hardly be accurate to describe the concerns over the environmental costs of energy development as "recent", even if it is true that wide public attention to these problems, as reflected in often tendentious reporting in the media, is recent. Throughout the seventies, experts, at least, had been discussing these problems (See e.g. M. Chatterji, Editor, Energy and Environment in the Developing Countries, Wiley, New York, 1981). Moreover, many developing countries began to create environmental institutions in the late 1970s: Sri Lanka's Central Environment Authority was established in 1980.

[4] See e.g. *Environment and Development: Implementing the World Bank's New Policies*, Development Committee Paper 17, World Bank, Washington, DC, 1989; or D. Giampaoli, *Policies and Strategies of the Interamerican Development Bank for the Energy Sector and the Environment*, Inter-american Development Bank, Washington, DC, 1988.

[5] M. Munasinghe, Integrated national energy planning in developing countries, Natural Resources Forum, 4, pp.359-73, 1980; and M. Munasinghe, *Energy Analysis and Policy*, Butterworths Press, London, 1990, chapters 2 and 3.

[6] For a good review of the principles of generation systems expansion planning, see e.g. International Atomic Energy Agency, *Expansion planning for electrical generating systems: A guidebook*, Technical Report 241, Vienna, Austria, 1984.

[7] In its modern usage in the United States, least cost planning has been defined a process which "..explicitly includes conservation and load management programs as capacity and energy resources; it considers environmental and social factors as well as direct economic costs; it involves public participation; and it carefully analyzes the uncertainties and risks posed by different resource portfolios and by external factors" (C. Goldman *et al. Least Cost Planning in the Utility Sector: Progress and Challenges*, Lawrence Berkeley Laboratory, Report LBL 27310, Berkeley, California, 1989.). The Electric Power Research Institute (EPRI) prefers the use of the term "integrated resource planning" to capture the idea of a balanced consideration of demand and supply side options.

[8] See e.g. E. Crousillat, *Incorporating risk and uncertainty in power system planning,* Energy Series Paper 17, Industry and Energy Department, World Bank, Washington DC, 1989.

[9] Although in Sri Lanka this has not been done until very recently, even in the case of projects with significant relocation costs. See Chapter 4 for further discussion.

[10] For a description of this model, see e.g. J. Nanthakumar, *Generation Expansion Planning in a Hydro Dominated System,* Paper presented at the Fourth RCA Workshop on Energy, Electricity and Nuclear Power Planning, Daejon, Korea, August 1990.

[11] For example, a recent ADB report on environmental considerations in energy planning first describes a comprehensive approach to the assessment of air quality impacts ("integrated framework of ensemble assessment", "systemic approaches" etc.etc.), but then, in a subsequent chapter that suggests what analytical approaches might in fact be undertaken, the assessment of air quality impacts is based on nothing more than a primitive scoring system based on emissions, justified on grounds that "the approach (that requires prediction of atmospheric impacts on receptors) has significant modelling implications, and is *beyond the scope of a study such as this"* [emphasis added].

[12] We review in more detail the procedures in use by American state regulatory commissions in chapter 5.

[13] See e.g. *Environmental Considerations in Energy Planning*, Asian Development Bank, Manila, May 1991.

[14] For example, the ADB report argues (p.4) that "..by contrast, a relatively stronger role is played by public investment in developing countries and this is a major factor determining the choice of approach.

In fact, in the absence of efficient markets and effective enforcement mechanisms for government regulation and revenue measures, investment decision-making may well be the most effective policy instrument developing country Governments have to influence the nature and location of economic activity and consequent environmental impacts".

[15] However, recent efforts in some countries to increase the role of the private sector in power generation do raise some important concerns in this regard. There is a significant danger that in the rush to attract private investors, and foreign investment in particular, promises to "streamline" and "accelerate" the clearance process in general, and environmental permitting in particular, through "one-stop" licensing procedures and the like, the temptation to gloss over environmental concerns may be very real. Yet it is almost inevitable that such concerns will emerge sooner or later. Delays (and especially litigation during construction) will be fatal to privately financed projects because of the high burden of interest during construction. Proper consideration of environmental concerns at an early stage of the planning process where private power is expected to play a significant role is therefore at least as important as in traditional models of largely public sector development of electric power.

[16] A. Markandya, Environmental costs and power systems planning, Utilities Policy, 1, 1990 p. 13-27.

[17] For example, MARKAL, an energy system optimization model, developed a decade ago under the auspices of the International Energy Agency, has been modified to deal with CO_2 emissions, and is being used in a number of developed countries to study technological options for greenhouse gas emissions control. For further discussion of the MARKAL model, see Annex. For a representative application of the model to a developing country, see e.g. Joint Indonesian-German Research Project, *Energy Strategies: Energy R&D strategies technology assessment for Indonesia*, Kernforschungsanlage Julich and Badan Pengkajian dan Penerapan Teknologi, 1988.

[18] However, Markandya notes that "..in practice, this model has not proved easy to apply, or particularly useful. None of the World Bank staff involved in the power sector used it" (Markandya, *op.cit.*, p.20). A new version of the IMPACTS module that is part of the ENPEP package has since become available, and is equipped with a modern user interface that makes it much easier to use than previous versions.

[19] A detailed discussion of IMPACTS is presented in the Annex that concludes this report.

[20] In this report we adhere to World Bank practice by using the term environmental assessment (EA) rather than environmental impact assessment (EIA), except where the latter is a direct quote. Environmental impact statement (EIS) has been used sometimes in Sri Lanka (and elsewhere) for the report that describes the findings of the EA, although the formal title of the report prepared for the Trincomalee thermal power project is "social and environmental assessment". In fact The National Environmental Act of Sri Lanka of 1980, as amended in 1988, uses the term "environmental impact assessment report" (Part IVc, Approval of Projects, section 23BB).

[21] For a broad review of the environmental assessment procedures in Asia see e.g. A. L. Brown, R. A. Hindmarsh and G. T. Macdonald, Environmental assessment procedures and issues in the Pacific - southeast Asia region, Environmental Impact Assessment Review, 11, p.143-156, 1991. Reporting on a workshop on EIA, the authors noted "... a perceived futility of some environmental assessments in terms of their ability to modify the project ...most construction projects starts before the EIA work begins ...the EIA work should begin at the planning stage of the project."

[22] Black and Veatch International (BVI), *Social and environmental assessment, Trincomalee thermal power project*, Report to the Ceylon Electricity Board, Colombo, Sri Lanka, 1988.

[23] "..it is therefore evident that the entire feasibility study process, terminating with the EIA, has followed a policy known as decide - announce defend... the EIS is an ex-post facto document seeking to environmentally justify a project which was formulated without any environmental considerations whatsoever .. this EIA is a post planning exercise, whereas it ought to have been an ongoing exercise from the inception of the project". Black & Veatch, *op. cit.*

[24] There are however many examples of where a project level environmental impact statement made claims that the impacts were acceptable, and that the project should go forward, but which in fact did *not* ultimately succeed. The classic examples here

include many nuclear power projects in the United States (such as Shoreham in New York, which, after an expenditure of over $5billion to construct the plant, was eventually sold to the State of New York for one dollar(!) without ever operating).

25 That the EIS is an inefficient vehicle for evaluating anything more than the very local site specific impacts is well illustrated by the American experience: because there was little if any public and environmental input to basic questions about the generation mix, EISs prepared for proposed nuclear plants proved to be the only focus for such input, resulting in long delays as fundamental questions on the generation mix, on the role of energy conservation, and on nuclear safety were endlessly re-examined.

26 Pace University Center for Environmental and Legal Studies, *Environmental Costs of Electricity*, Oceana Publications, New York, 1990; p. 633.

27 P. Meier, *ENVIROPLAN: A multi-attribute environmental simulation model for energy and power systems planning*, Environment Department, World Bank, Washington, DC, 1994.

2. METHODOLOGY

The methodology developed in this case study consists of the following steps:

1. Identification of the technology, pricing, siting and the major pollution mitigation options to be examined.
2. Identification of the environmental issues that are of concern to power sector policy-makers, and categorization into issues that are quantifiable, and those that are not.
3. For those attributes where quantification and economic valuation is possible, explicit valuation of the relevant externalities and incorporation into the system cost attribute.
4. For quantifiable attributes that cannot easily be valued economically, definition of attributes to be used in the multi-attribute analysis.
5. Display and examination of the trade-off space, with a view to providing the decision-maker an understanding of the trade-offs that are inherent in the selection of particular options.
6. Application of decision rules to identify superior strategies, and to eliminate clearly inferior options.

Each of these major steps warrants some initial discussion: obviously these themes are developed in more detail in later sections of this report. Figure 1.1 depicts the sequence of analysis required.

1. Identification of options: The first step, obviously, is to define the universe of options to be addressed. In fact a great deal of care must be taken in any preliminary screening exercise. Some exclusionary screens can be applied with great confidence: no facilities in designated wildlife sanctuaries, no nuclear plants in areas of known geological faults, etc. However, many other screens routinely applied by engineers in a siting study involve judgements that may reflect only some personal viewpoint (even if supported by personal experience): such as a presumption that a coal-based plant must be "near" its coal receiving port. What does this really mean? Obviously there are costs associated with intermediate truck or conveyer belt transport, but these have to be put in the context of other costs associated with particular sites.

Indeed, it is very important that as few *a priori* judgements as possible are made about the "feasibility" or "practicality" of options, because for the analysis to be useful, meaningful trade-offs must be examined. For example, in the case of the proposed Trincomalee coal fired power plant, the environmental impact assessment prepared in the mid 1980s considered only a very narrow range of options: all alternatives studied involved sites on Trincomalee bay, with once-through cooling to a shallow bay. Other sites had been eliminated on grounds of high cost (because sites on the south coast, for example, cannot accommodate large coal transport vessels, resulting in higher transport costs). Yet the additional costs of an

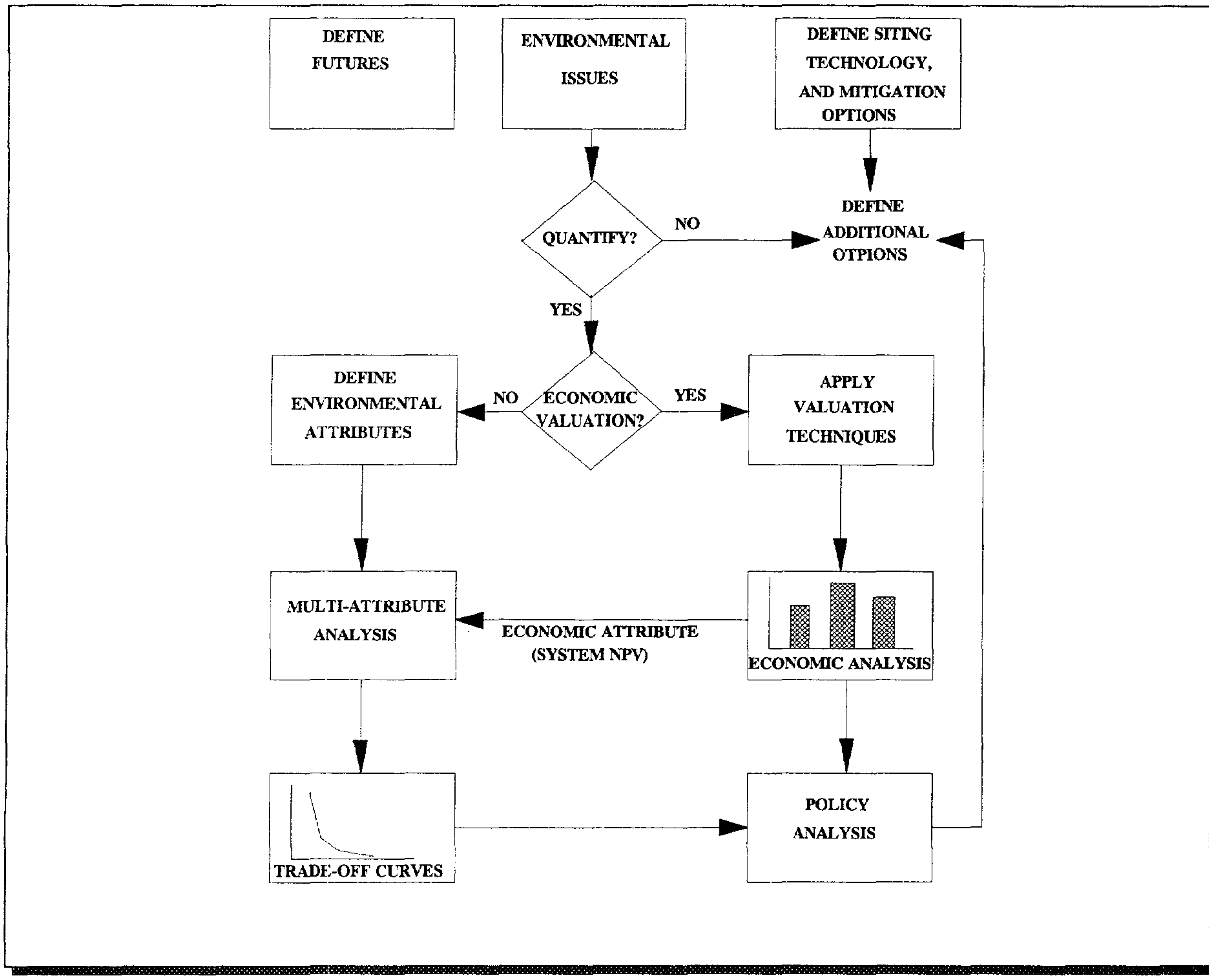


Figure 2.1: The general methodology

evaporative cooling system, or of an outfall system that would discharge heated effluents to the deeper parts of the Bay, proved to be less than the incremental coal transport costs to a site on the South Coast.

2. Identification of the major environmental issues: Although this is a relatively straight forward step, some care needs to be exercised in the issues chosen for inclusion for analysis: they should reflect issues of national (as opposed to local project level) significance, and ought to be limited in umber. There is little to benefit from proliferation of issues and attributes. Increasing the number of attributes is not a substitute for assigning proper weights to environmental attributes in the subsequent decision process.

On the contrary, the more attributes considered, the more complex the analysis, and the higher the probability that the results will be hard to interpret and that decision-makers will not find the exercise useful. It often occurs that, in a desire to be comprehensive, there is an inclusion of all possible impacts, making it more difficult to demonstrate trade-offs, and possibly introducing biases through a reluctance to assign low weights to attributes.

3. Economic valuation: In any general situation, there will be certain environmental impacts for which economic valuation poses few difficulties, and/or where application of well established procedures is not likely to be controversial. Use values in particular pose relatively few difficulties in this respect. Thus estimating the opportunity costs of lost production of land inundated at a hydro plant, or estimating the benefits of a potential reservoir fishery, pose relatively few problems.

Unfortunately a number of the important impacts associated with the power sector do pose major difficulties, perhaps most importantly those associated with the health impacts of fossil fuel combustion. Clearly the most difficult valuation issue concerns the value of human life, and the economic cost of illness. Indeed, as one reviews the literature, it is clear that a substantial fraction of the environmental damages associated with particulate, SO_2 and NO_x emissions are related to health impacts and visibility impairment. American valuations of these impacts indeed suggest damages that are higher than the costs of pollution control now imposed by American standards. Whether that is true for developing countries is an interesting and important question, and indicates the need for some country-specific contingent valuation studies to establish the willingness to pay to avoid illness.

In general, we are of the view that where valuations involve a high degree of uncertainty, one is better off not to attempt them, and simply use the physical impact quantification in a subsequent multi-attribute analysis of trade-off curves. In this study, therefore, we have avoided use of dose response functions in the multi-attribute analysis, but simply use the population-exposure to specific pollutants as the proxy for health damages. In any event, since the main purpose here is to provide a basis for comparison of practical options, rather than establish some absolute measure of impact, the population exposure measure still provides a great deal of relevant information about the health effects of alternative options.

4. Selection of environmental attributes: To some extent, of course, the physical quantification is not unrelated to the selection of attributes: clearly there is not much point in selecting criteria that cannot be quantified. That of course does not imply that only quantifiable criteria are relevant or important: it means only that such unquantifiable criteria need to be considered through some other means.

As an example, the health impacts associated with exposure to very high voltage transmission lines may be viewed as significant.[1] There is presently no basis for quantifying that health effect. Therefore, the way to include an assessment of the issue is to define a technology scenario that eliminates the need for EHV transmission (for example by moving the baseload coal plants from the remote areas in the South and Trincomalee to the major load center in Colombo), and then asking whether one is willing to incur the incremental health costs of this option (associated with exposure to fossil plant air pollutants) in order to avoid the health impacts of EHV transmission.[2]

Finally one might note that attributes should reflect issues of national (as opposed to local project level) significance, and ought to be limited in number. There is little to benefit from proliferation of attributes. Increasing the number of attributes is not a substitute for assigning proper weights to environmental attributes in the decision process. On the contrary, the more attributes considered the more complex the analysis, and the higher the probability that the results will be hard to interpret and decision-makers will not find the exercise useful. It often occurs that, in a desire to be comprehensive, there is an inclusion of all possible impacts, making it more difficult to demonstrate trade-offs, and possibly introducing biases through a reluctance to assign low weighting to attributes.

The problems of quantification are well illustrated in the case of the biodiversity attribute. At the planning level, detailed site specific information at the potential power plant sites is unlikely to be available. Consequently the only quantification that appears possible is to derive a probabilistic index that gives the decision-maker information about the likelihood that the detailed environmental impact statement will reveal the presence of an endemic species, significantly impact ecosystems of high biological diversity, or affect a habitat already in a marginal condition.

There are a number of practical problems in deriving an appropriate index. The first is that the value of the area lost is a function what remains of the habitat. For example, the loss of the last hectare of an ecosystem would be unacceptable, whereas the loss of one hectare if 1,000 hectares remain would be much less.

Second, ecosystems may require a minimum area for long term survival, which implies that the value function would need to tend to infinity as it approaches that minimum value. Perhaps even more importantly, the argument is sometimes made that the value to be ascribed to the loss of habitat associated with some regulatory or governmental decision depends on the extent to which the remaining area remains secure from further encroachment.

Other impacts, however, resist direct quantification, even in terms of the sort of probabilistic scale derived for biodiversity. For example, the quantification of potential damages to aquatic ecosystems from thermal discharges is extremely problematic, in large part because of the difficulties in extrapolating from one ecosystem to the other. The general effects of thermal discharges into coastal waters are of course well known. Discharges into the well-mixed, surface layer would usually have the general tendency to repel fish. On the other hand, if the discharge is below the thermocline, thermal discharges would have a generally beneficial effect, as the up-welling effect caused by plume buoyancy brings nutrients to the layers near the surface. However, attaching specific numerical estimates to the values of this general function is essentially impossible. What can be done as a generic calculation that can be used to compare different sites is to begin with a definition of what is considered to constitute an acceptable environmental risk; for example, say a temperature increase of no more than 1°C at the surface. The surface area over which this criterion is exceeded is then calculated as a function of the cooling system design proposed.

5. Multi-attribute analysis Multi-attribute analysis has been developed expressly for situations were decisions must be made upon more than one objective which cannot be reduced to a single dimension. Its central focus is the quantification, display and resolution of trade-offs that must be made when objectives conflict. Most important in this is to provide decision-makers with relevant information, if at all possible in the form of graphical displays (such as trade-off curves).

6. Decision rules: There are a number of reasons to avoid the use of formal decision rules at this stage of environmental debate in Sri Lanka. For example, we might have ranked the policy options studied using a weighting summation rule to derive an overall merit score for each strategy. However, that would inevitably force attention on whether or not our weights were correct, or whether we had elicited weights from the appropriate group of decision-makers. Exclusionary screening, which is extensively used in power plant siting, is in effect a multi-attribute decision rule.

Rather, we believe that for those countries where the process of setting clear environmental priorities are still at a very early stage, the first step is to first try to focus on the nature of the trade-offs themselves, and to attempt to identify policy options that are robust with respect to the many uncertainties that arise, and that may be completely independent of what economic values are attributed to environmental externalities, or what relative weights are placed on particular impacts. Of course it is unlikely that options can be found that are completely dominant -- meaning they are best across all criteria. Nevertheless, as we shall demonstrate, certain policy and technology options -- such as demand side management measures and certain clean coal technologies -- do appear to be desirable from both environmental and economic perspectives over a wide range of conditions. One can also identify options that are clearly inferior, and that can be safely excluded from further consideration. The remaining chapters of this study are aligned very closely to the principal steps in the methodology as illustrated on Figure 2.2.

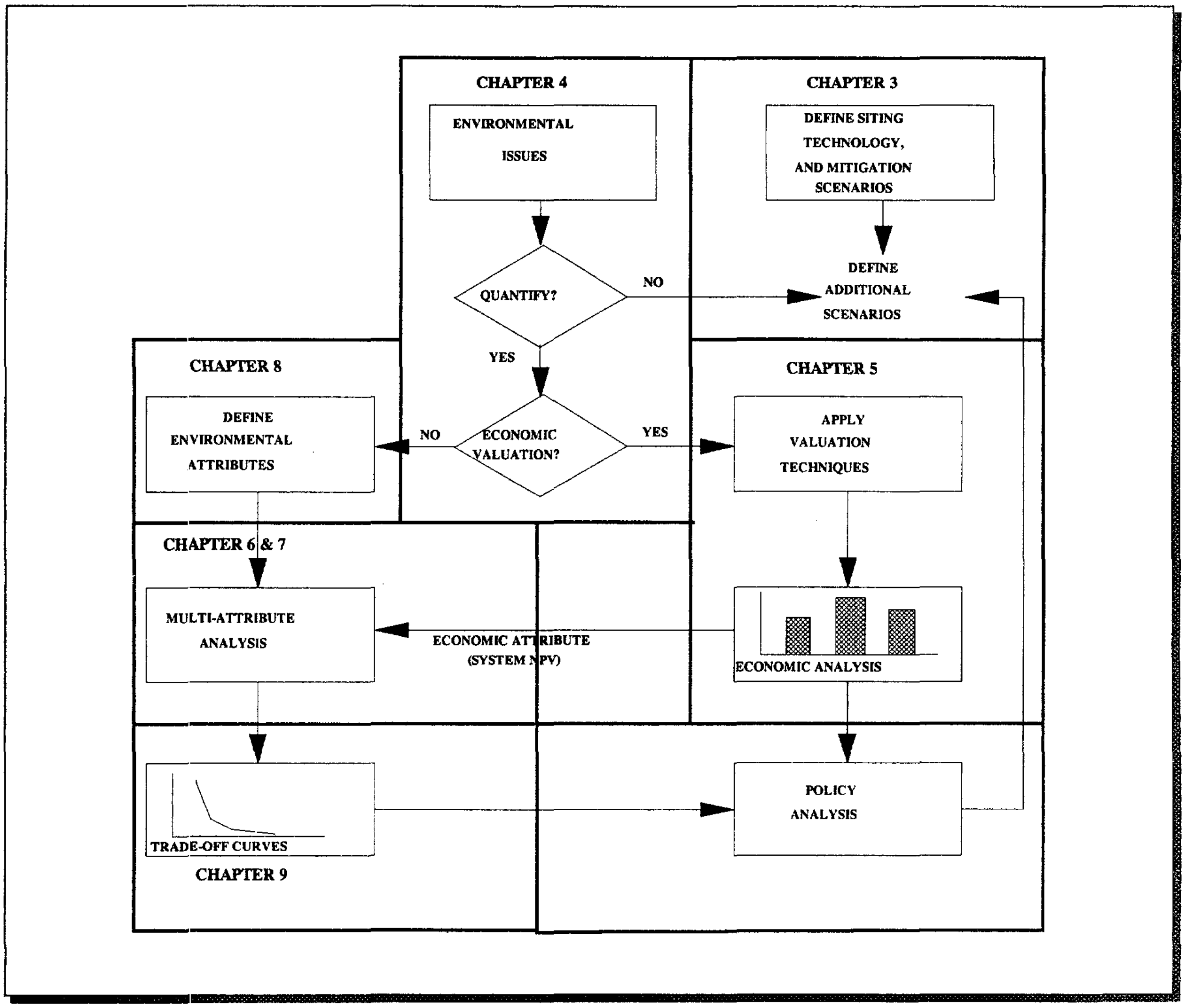
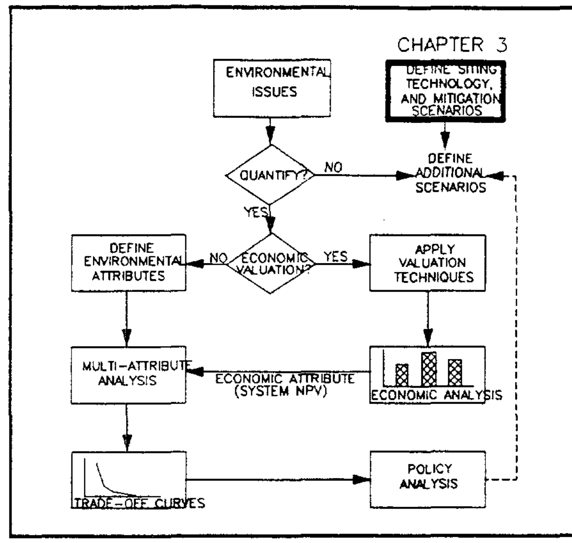


Figure 2.2: Organization of the study

Notes

[1] For a good review of this particular issue, and the uncertainties involved, see e.g. H. Florig, Responding to potential health effects of electric and magnetic fields, Resources, Fall 1992, 109 (Resources for the Future, Washington, DC).

[2] A second possibility is to use so-called hedonic valuation techniques, as discussed later in Chapter 5.



3. DEVELOPMENT OPTIONS

The first step in any sectoral study of environmental impacts is to define the options for system development. This may include technology options, fuel supply options, siting options, and the major systemwide mitigation options (such as a potential requirement for flue gas desulfurization systems at coal plants). Before defining the set of options as study scenarios, we begin with a brief review of the historical development of the power system, and of the constraints and problems faced by power system planners in Sri Lanka.

Development of the system to the early 1980s

The recorded history of electricity development in Sri Lanka began on December 6, 1894, when a sum of Rs. 80,000/- was allocated by the Ceylon Legislative Council for the electric lighting of Queen's House and the General Post Office. Shortly thereafter, in 1895, "an Ordinance to provide for the protection of persons and property from the risks incidental to the supply and use of electricity for lighting and other purposes" was enacted. In the same year, the firm of Boustead Brothers started supplying direct current electricity to consumers in parts of Colombo. Piped coal gas, used for street lighting since 1872, found electricity a strong competitor, and by 1899 electric tramways had been introduced in Colombo. As the demand rose, the Colombo Electric Tramways and Lighting Company was formed in 1902 and acquired a power station at Pettah.

The first hydro plant was installed in 1912 at Blackpool to supply Nuwara Eliya. This scheme functioned successfully and electricity was extended from this plant to the railway station at Nanu Oya in 1913. About this time, as recorded in Ferguson's Directory of 1913, annual imports of fuel to the country were around 800,000 tons of coal and 10 million gallons of oil. Factories processing tea, rubber and coconut reported capacity of 3500 Hp; others, including electric plants, reported an installed capacity of 16,705 Hp. In the same year, 644 steamships were coaled in Colombo harbor; the other major user of coal was the railways.

Serious attention to the development of hydropower began in 1918, when a Mr. Wimalasurendra, a district engineer of the Public Works Department (PWD), presented a paper to the Engineering Association of Ceylon. Briefly his recommendations were to harness the Mahaweli and Kelani Ganga hydro potential and utilize such power for industrial uses, railway electrification, and the manufacture of calcium carbide and calcium cyanide. Based on this proposal, a start was made in 1924 to install the first dam at Norton Bridge with a power station at Laxapana, but due to unforeseen difficulties work was suspended in 1927. However, a one Mw plant erected for the construction facilities was completed and this supplied power to the area.

In 1928, the government decided to acquire the facilities maintained by the Colombo Electric Tramways and Lighting Co., and transfer operation to a government department. In 1929, a new power station equipped with two 3 Mw steam turbines was commissioned at Kolonnawa and named the Stanley Power Station after the then governor. Two more 3

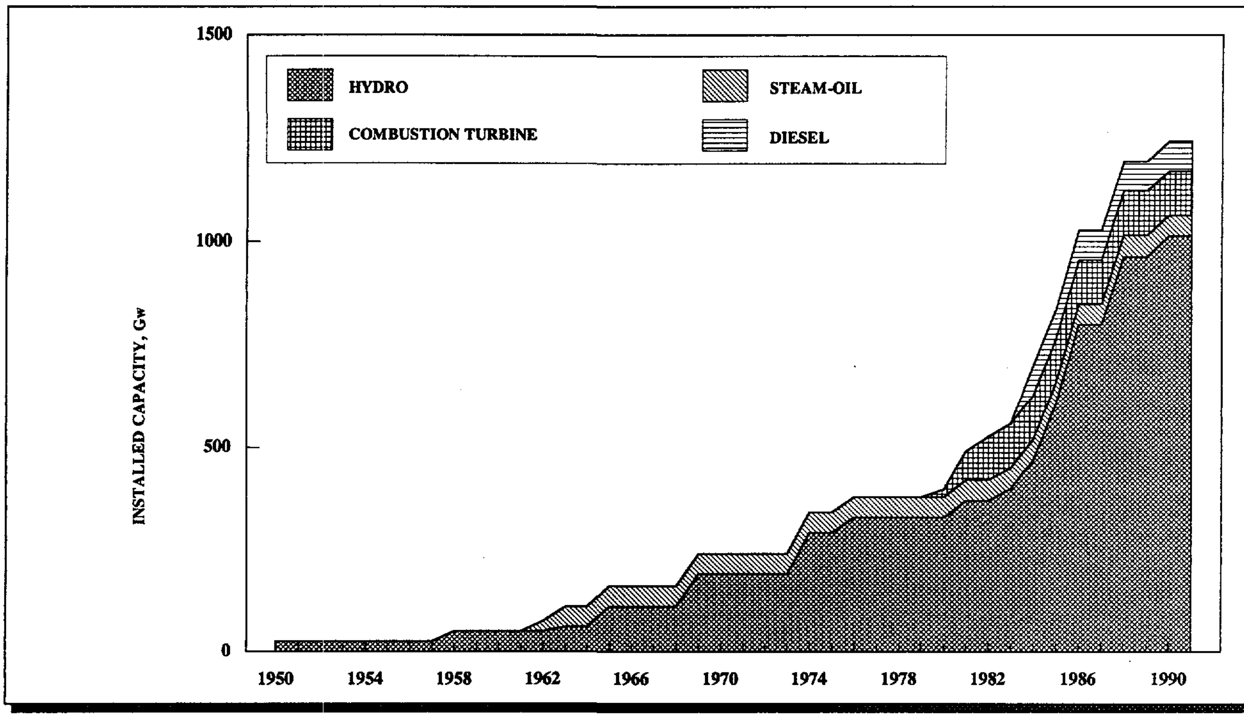


Figure 3.1: Installed capacity in Sri Lanka

Mw steam turbines were added, one at Stanley Power Station and one at Pettah. These facilities helped to meet the increasing demand not only in Colombo but made it possible for a few suburbs and towns to obtain cheaper electricity supplies and retire existing plant. However, expansion of electricity supply to other areas was slow, and at the end of 1929, only 16 towns had electricity distribution.

In 1935, the government Electrical Department (DGEU) was converted by statute to the Electricity Board of Ceylon, but for some reason, the Board was dissolved in 1937 and DGEU was re-established. The hydro scheme at Laxapana was revived in 1940, but the World War affected progress because of lack of equipment available for civilian needs. However due to the strategic importance of Colombo, it was possible to obtain three 1 Mw diesel plants for the Pettah power station. A diesel unit in Wellawatta operated by the British Navy also helped to tide over this difficult period. The 25 Mw Laxapana hydro scheme, connected by 66 Kv transmission lines to Colombo and Kandy, was finally completed in 1950. In 1954 World Bank funds were used for the first time to fund a second stage that added an additional 25Mw.

In the mid fifties the DGEU realized the need to plan the development of the hydro potential and a special unit called the Hydro Development Branch was set up. United Nations assistance was obtained to engage a hydro power specialist who investigated some 22 sites and identified projects such as Victoria, Randenigala, Seven Virgins, Samanalawewa and Ratnapura. This was the first systematic attempt in assessing the power potential from hydro sources. In 1969 the Ceylon Electricity Board was established as the successor entity to DGEU.

Over the next 20 years a number of further hydro units were added to the system, as illustrated on Figure 3.1. By 1975, the installed capacity had reached 342 Mw, of which 292 Mw was hydro. But until the accelerated Mahaweli development program, and the start of the major projects at Kotmale and Victoria, few questions of environmental impact were raised.

As the transmission grid began to expand in the 1960s and 1970s, the general strategy was to keep transmission corridors as much as possible away from developed and populated areas. At

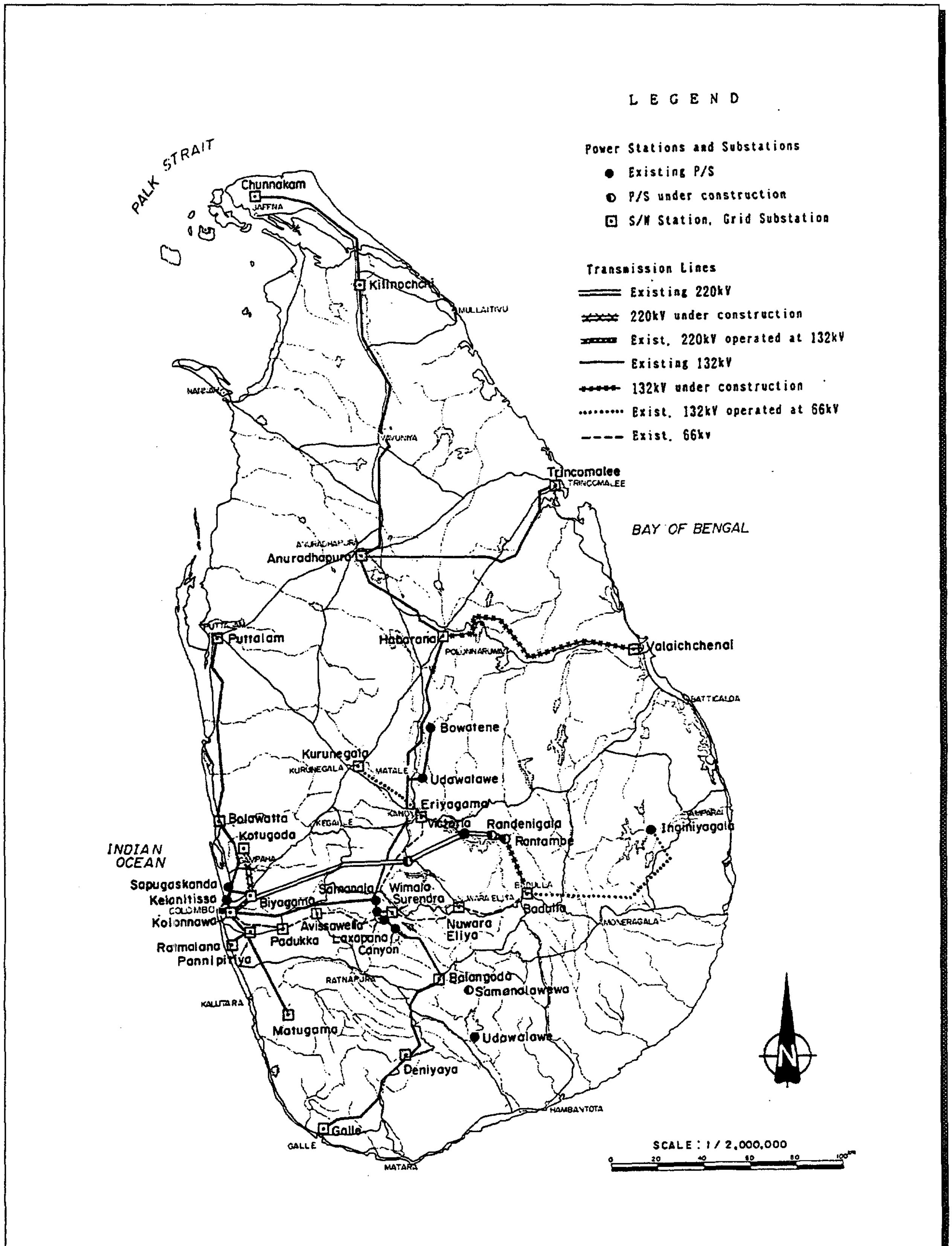


Figure 3.2: The present CEB system

this time, placing of transmission lines over forest land was preferred, although some instances can be recalled where deviations had to be made to avoid Sigiriya archaeological sites. The effect of transmission lines on tea lands was also deemed negligible by the CEB at that time. In the case of transmission lines traversing coconut and rubber lands, a standard width of 120 feet was required to be cleared.

The 132 Kv line to Jaffna, built in 1970, was expressly routed across forest land to avoid developed areas. The 132 Kv line to Galle had to cross virgin forest land between Upcot and Balangoda, and was even routed through the Sinharaja forest, now one of the remaining rich rain forest areas, although even at the time this was opposed by the forest authorities. The intention at the time was to save cultivated land. In the case of the Laxapana complex, some 1,160 acres of rubber, 1,760 acres of coconut and 2,570 acres of forest land were cleared of vegetation for the required 66 Kv and 132 Kv transmission lines.

In the mid 1970s unsuccessful attempts were made to undertake the Kotmale hydro project with assistance from India, with payment in kind through a power linkage to Southern India. Negotiations were also started with the USSR for the construction of the Samanalawewa Project, but these were incomplete when the new government entered in 1977. This new administration introduced a series of economic reforms in the late 1970s that resulted in a rapid increase in economic growth rates and in the rate of growth for electricity. By the late 1970s CEB faced serious power shortfalls that were exacerbated by drought that continued into the 1980s.

The 50 Mw Kelanitissa steam plant, completed in 1962, ran erratically due to intermittent use. In anticipation of power shortfalls, 60 Mw of combustion turbines was installed in 1981, subsequently increased to 120 Mw in 1982. The high costs of running these units were recovered by fuel surcharges, but many local authorities found this measure burdensome and were reluctant to collect these additional charges. Arrears due to the CEB from local authorities, which had accumulated over several years, thus increased even further. Several attempts to recover such arrears failed and the Treasury had to make good these losses directly to the CEB.

These events put pressure on the early commissioning of the Swedish-funded Kotmale power station, now the first project in the cascade of the accelerated Mahaweli programme. The 220 Kv line contractor defaulted and the CEB had to make alternative arrangements to absorb power to the CEB grid. Moreover, technical problems arose in the pressure tunnel that supplied the underground power house, and the plant had to be closed for installation of steel linings to the tunnel to prevent leaks. The other accelerated Mahaweli projects, at Victoria, Randenigala and Rantembe had a relatively smooth passage; the former funded by the United Kingdom, the latter from several sources including grants from Germany.

Coal-fired generation

The Ceylon Electricity Board had realized from its very early days that hydro power alone would not be able to satisfy increasing electricity demands. In any event, the natural variability of rainfall in Sri Lanka is such that an all-hydro system would require large excess capacity to meet the demands in drought years.

After the second oil price shock of the late 1970s, throughout the world oil fired plants were being converted to coal, and it became clear that the most appropriate choice for future baseload generation in Sri Lanka would be coal. In the early 1980s, approaches were made to the Australian government for assistance, and in 1982 the Australian firm Crooks Michel Peacock Stewart was commissioned to conduct a preliminary pre-feasibility level study for coal power in Sri Lanka with funding from the Australian Development Assistance Bureau (ADAB).

This study pointed to the desirability of importing coal in large 150,000 ton vessels to minimize freight costs. The only harbor in Sri Lanka which could handle such shipments is at Trincomalee, which is one of the best natural harbors of the region, and the study recommended this as a site for up to 1,000Mw of ultimate capacity. Subsequently, the CEB

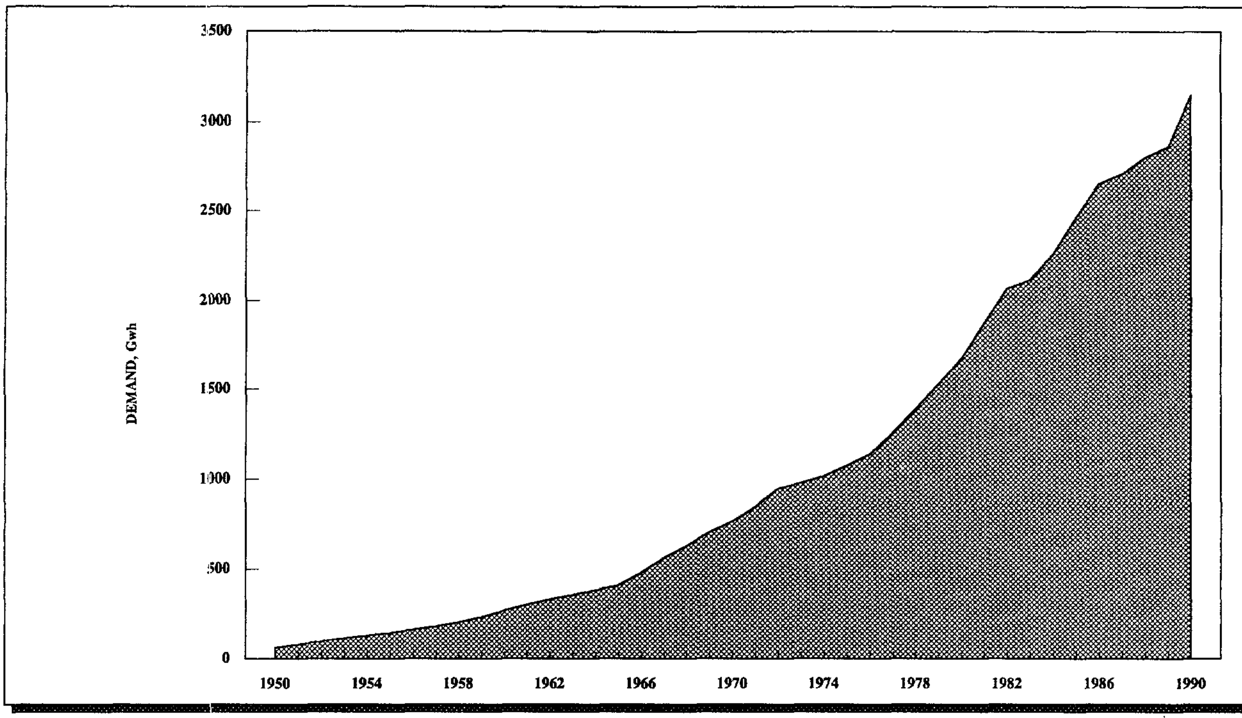


Figure 3.3: The demand for electricity in Sri Lanka, 1950-1991

sought Asian Development Bank (ADB) assistance for a full feasibility study, and a $5million soft term credit was provided. Black and Veatch International of the United States was selected for the study, and they commenced work in 1984.[1]

The study examined four possible locations in the Trincomalee area. Of the four sites, the site at Snug-Cove was recommended as the most appropriate and cost effective; its cost was some Rs1,000 million less than that of its closest competitor.[2] However there were objections to the choice of this site from the chairman of the National Aquatic Resources Agency (NARA) and others. In order to analyse these objections, the President of Sri Lanka appointed a team of officials in 1987, comprising the Secretary of Finance, the Chairman of the Central Environment Authority, the Secretary of the Ministry of Power & Energy, the Chairman of the Ports Authority, and several others. After a detailed study, this committee recommended that the coal project should proceed as recommended by the Black & Veatch study.

Nevertheless a series of further objections were raised by NARA and by environmental NGOs. Any project in the coastal zone requires approval of the Coast Conservation Department, who in the end made a determination that the project could not be permitted in the form it was presented. The CEB appealed this decision under the statutory provisions of the Coast Conservation Act, but was turned down. The question of alternative options, particularly with respect to cooling systems that would minimize the thermal plume impacts that was one of the deciding factors, is one that will be taken up later in this report.

However, by late 1987, CEB's immediate interest in the coal plants had diminished considerably. In 1986, the world price of oil dropped precipitously, and for several months the price of heavy fueloil, on an equivalent Btu basis at the burner tip in a steam cycle plant, was cheaper than coal. By the time of the 1987 generation plan, heavy fueloil was in the $14-16/bbl price range, and the economics of diesels looked fairly attractive vis-a-vis those of coal. Perhaps equally important, the civil disturbances had considerably reduced the rate of growth of demand for electrical power and energy. The rate of growth, which was as high as 10% per annum previously, was reduced to about 3% per annum. Thus the 1987 generation expansion plan did not project a coal unit as being needed until well beyond 2000. Finally, the surroundings of Trincomalee became very unsafe due to terrorist activities; ensuring the transmission of electrical power from Trincomalee through thick jungles to Anuradhapura or some other location to reach the main electricity grid would also have been very difficult.[3]

However, there remained some available soft term credit from the Asian Development Bank, and the Ceylon Electricity Board extended the Black and Veatch study to cover alternate thermal plants elsewhere in the country. This became known as the "Thermal Options Study",[4] which examined a number of alternative coal plant sites, narrowed down to the Matara area on the south coast and a set of sites north of Colombo. But the 1989 and 1990 generation plan studies came to conclusions not much different: coal units would not be required until after the year 2000, with smaller diesel units emerging as the better choice over the immediate future.

The proposal for a coal plant on the south coast was met with equally vehement opposition. Although the Central Environment Authority had drafted terms of reference for an environmental assessment of a coal plant at a south coast site, the government decided in 1990 that coal power development in this area should also be suspended, and the assessment was never conducted.

In the 1991 generation study, however, the first coal unit is projected as being required in 1999, and in the base case the only new hydro plant in the least cost plan is the 40Mw Broadlands project. In the no coal option, Ging Ganga (49Mw) and Uma Oya (150Mw) are also in the plan, baseload units being exclusively diesel. This no coal option has a levelized kwh cost that is 7% higher than the base case. In later chapters we analyze the environmental implications of these various options in some detail.

Future Options

This case study is about the environmental impacts of alternative development paths for the electric sector, and how they might be incorporated into decision-making. Thus it is very important to have examined the widest possible range of options for the future. As much as possible one ought not to exclude certain options on intuitive grounds, it being the purpose of the analysis to display the trade-offs to be made by the decision-maker.

There has been a traditional reluctance on the part of power sector planners to consider seriously a wide range of alternatives to the conventional supply side expansion approach to sector development. Many of these options then become part of the debate raised by the environmental community at the stage of project approval, where they become very difficult to address meaningfully. It is quite important, therefore, to include them in an early stage of the planning process, even if it is true that some of these options may have limited scope, or are more costly than conventional supply side generation technologies. What is important is that they all be considered on an equal playing field, and that the trade-offs are quantified and displayed. Even from the perspective of the supply side expansion advocate, it is surely much better to have analyzed an expensive renewable technology, and then be able to have quantified the trade-off, than not to have done the analysis in advance, and then be left open to criticism at the project stage.

In this case study, time and resource constraints prevent us from examining all these options. Rather, the approach taken is to consider representative examples of each type of potential option. In the case of renewable generation technologies, we use wind as the example; in the case of efficiency improvements, we use further reductions of T&D losses as the representative example, and so on.

Absent the discovery of oil or natural gas, the conventional wisdom is that for the next twenty years the generation options for Sri Lanka are quite limited. While substantial hydropower resources could be developed, the remaining sites are limited in size, and have substantially higher costs than alternative options (see Table 3.1). Moreover, even if nuclear power were economic, the size of the system is such that a 600-800Mw nuclear unit could not be accommodated until 2010, at the earliest.[5] The commercial availability of new reactor designs such as modular, fail-safe units of 100-200Mw, that could be accommodated into smaller systems, also seems at least 10-15 years away. The basic choice thus amounts to one between hydro, imported coal and diesels.

Table 3.1: Specific generation costs

project/plant	capacity Mw	specific costs, USCents/ Kwh
hydro		
Ging ganga	49	4.69
Broadlands	40	4.92
Upper Kotmale	248	5.26
Uma oya	150	5.33
Moragolla	27	6.35
Belihul oya	17	7.72
Kukule	144	7.89
thermal		
coal (70%PF)	300	4.50
diesel (70%PF)	20	6.20
combustion turbine (20%PF)	22	11.5

Source: CEB Report on Long Term Generation Expansion Planning Studies, 1992-2006, September 1991.

As a result of a close re-examination of the historical hydrological records, the assumptions for hydro energy availability have been revised downwards by the CEB. The result is that in the 1991 generation planning study, total hydro energy of existing plants has been reduced from 4070 gwh to 3869 gwh, and projected energy from the new plants have been similarly revised, as indicated on Table 3.2.[6]

These changes in hydro assumptions, and the differences in the relative fuel prices between residual oil (the fuel used in diesels) and coal, have a dramatic impact on the optimal generation mix as determined by the WASP model-- as indicated on Figure 3.4. This shows

Table 3.2: Average hydro energy assumptions, Gwh

plant	1990 study	1991 study
Existing plants	4070	3869
New plants		
Ging Ganga	206	194
Morgolla	111	111
Kukule	512	398
Broadlands	170	145

(existing plants include Samanalawewa)

capacity additions built in the periods through 2000 and 2005. As one might expect, given lower hydro energy, fewer hydro plants are built in the 1991 study. But the most dramatic difference is the mix of diesels and coal plants; in the 1991 study coal some 900Mw of coal fired plants are estimated to be required by 2005, as opposed to only 300Mw in the 1990 study. The differences in the environmental impacts that follow from these two very different generation mixes are obvious.

Demand side options

The potential contribution of demand side management (DSM) options have become increasingly apparent over the past few years. In industrialized countries such as the United States, the approach known as integrated resource planning, in which demand and supply side options are considered on an equal basis, is now standard practice. In developing countries, there is a growing awareness of the possible role of DSM, even in systems where growth rates of demand are much higher than those experienced in the industrialized countries.

The approach to an examination of the DSM potential and its environmental impacts taken in this case study is to begin with the official 1991 base case projection of the CEB, as shown on Figure 3.5. We do not use the low demand case to reflect DSM, because it embodies a wide range of assumptions, particularly for GDP growth rate, other than just the impact of conservation. Instead, we perturb the base case projection by considering very explicitly the technological and load curve consequences of specific DSM measures.

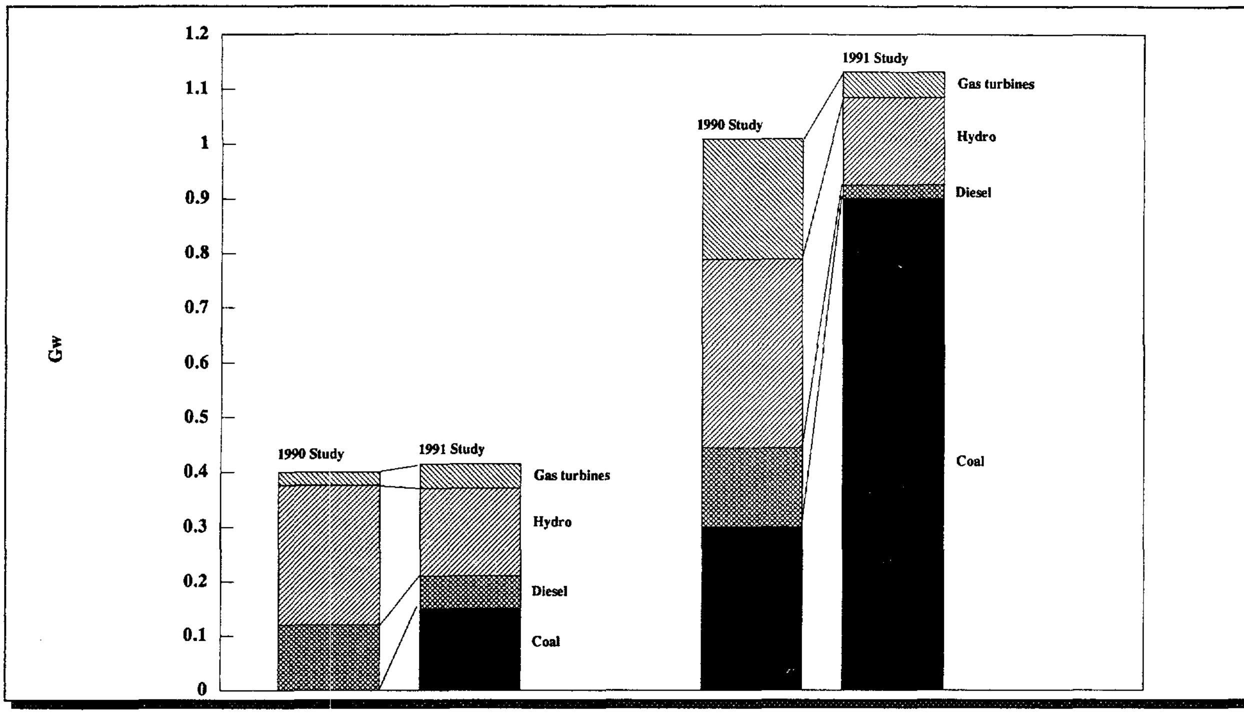


Figure 3.4: Generation mix options in the 1990 and 1991 CEB planning studies.

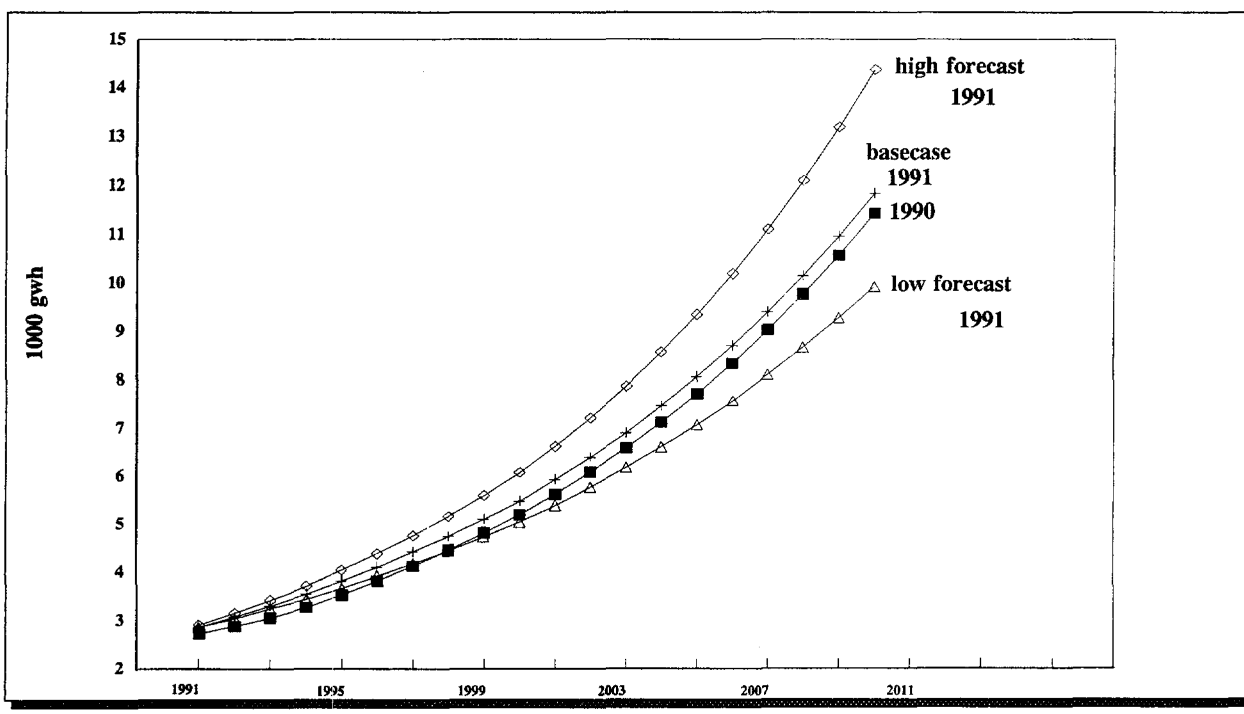


Figure 3.5: demand projections.

Source: CEB Generation Plans, September 1991 and 1990.

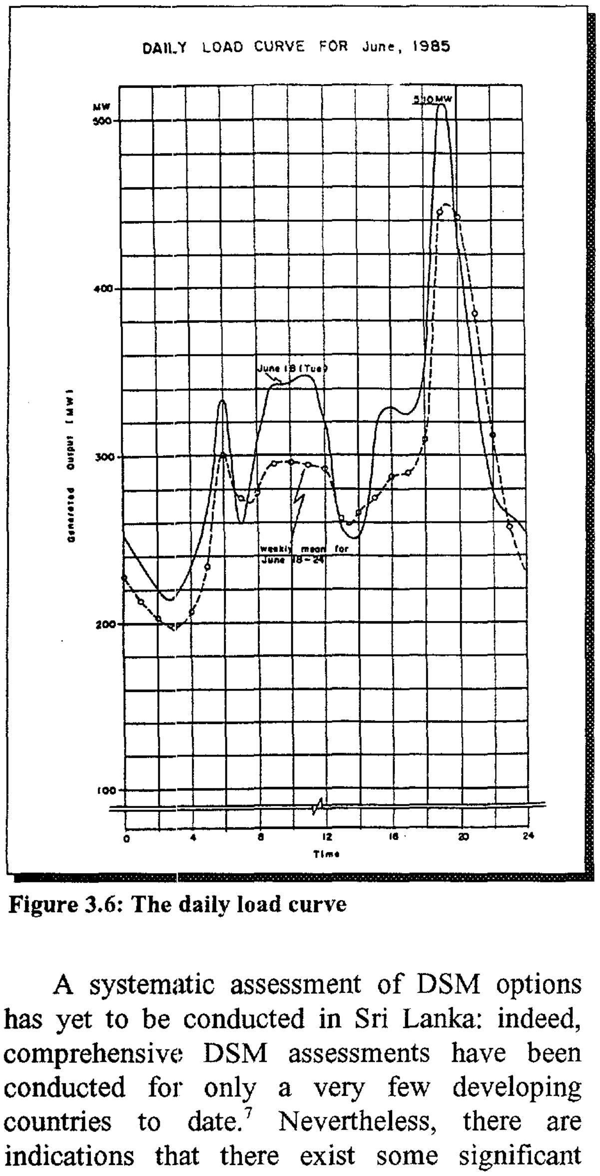


Figure 3.6: The daily load curve

A systematic assessment of DSM options has yet to be conducted in Sri Lanka: indeed, comprehensive DSM assessments have been conducted for only a very few developing countries to date.[7] Nevertheless, there are indications that there exist some significant opportunities for the introduction of energy efficient end-use technologies in Sri Lanka. Both the World Bank power system efficiency study of Sri Lanka[8]and the GTZ Masterplan made some preliminary estimates of the potential for load management and energy conservation by the systematic replacement of incandescent lamps by fluorescent lights.[9] This measure is therefore used in this study as the illustrative DSM example; the analytical framework is capable of analyzing other potential DSM measures in a similar way.

Of some interest from an environmental standpoint is also the question of railway electrification. For many years the railway department of the government has been in the practice of buying rolling stock in packages every 4 or 5 years, at which time the question of electrification is always raised, then to be forgotten after the new rolling stock arrives until the next cycle. With increasing urban air pollution in Colombo caused largely by motor traffic, the environmental advantages of electrification are twofold: not only would the diesel locomotives themselves be replaced by electric locomotives, but a modern electrified urban rapid transit system would likely reduce a significant number of diesel buses which are a major contributor to Colombo's air pollution problems. On the other hand, if the electricity for railway electrification is generated by oil and coal, there will likely be some offsetting environmental disadvantages; nevertheless, in general it is much easier to control emissions at a few central points. In this study, however, the impact of a future railway electrification is not considered.[10]

Power System Efficiency: T&D loss reduction

One of the most important ways of reducing the environmental impacts of power sector development is to ensure that the technical efficiency of the system is at its economically efficient value. For example, a T&D system that has only 2% losses might certainly be technically feasible, but would entail the use of technology (such as superconducting transmission) that is prohibitively expensive. On the other hand, loss rates of 20% and more, commonplace in some developing countries, are clearly also economically inefficient, and investments to reduce losses by rehabilitation of the T&D system are frequently justifiable on economic grounds alone. But if technical losses are reduced, then to produce the same level of benefits to consumers, less fossil fuel will be required to produce these same benefits, and pollution emissions will decrease (per unit of benefit to society). It should be noted that this reasoning applies only to the reduction of technical losses. Therefore, the environmental consequences of reduction non-technical losses through improvement of collection procedures, elimination of pilferage etc. will depend upon assumptions made about the resulting financial

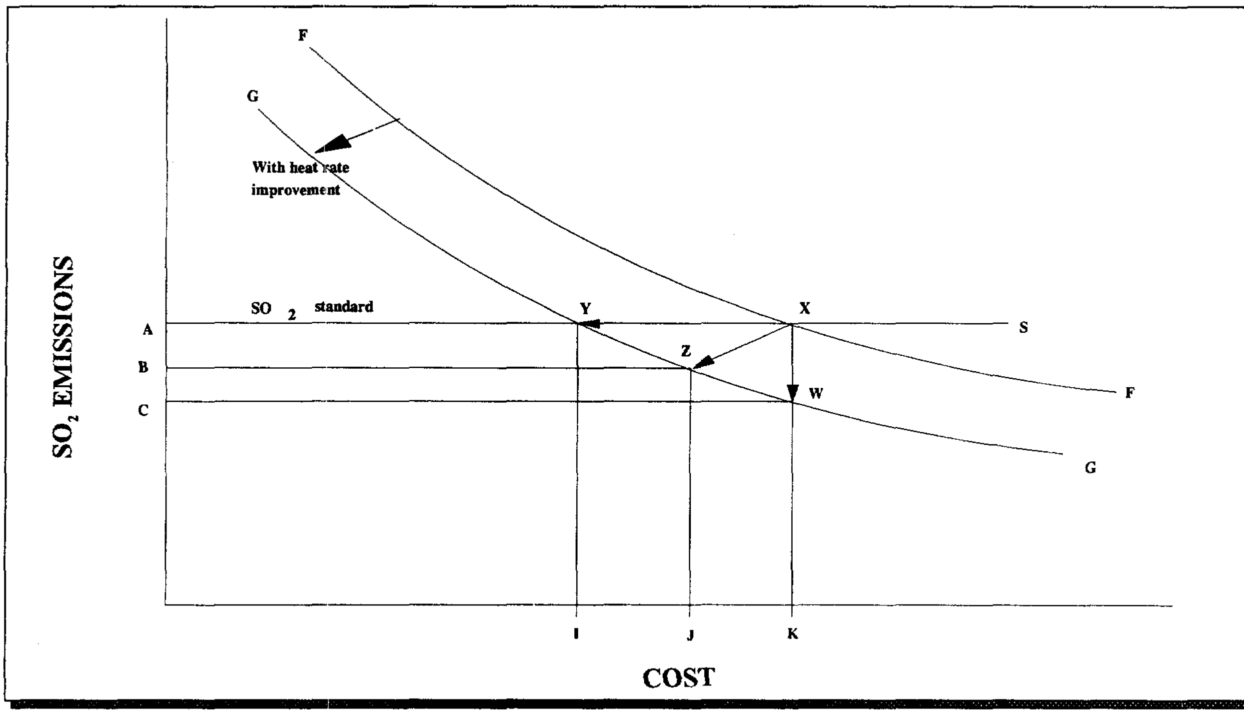


Figure 3.7: The impact of efficiency improvements

impact on the utility, and on the price elasticity of demand. If for example improved revenue collection eliminates the need for a tariff increase in order to meet given balance sheet ratios, then overall consumption would tend to increase (given normal price elastic behavior). On the other hand, with the same assumptions about price elastic behavior, consumers who were forced to pay for previously pilfered consumption would presumably reduce their consumption.[11] On balance one suspects that these effects largely offset each other, with the result that it is primarily the reduction of technical, rather than non-technical losses that has a direct environmental benefit.

However, whether or not efficiency improvements do in fact lead to environmental benefits is illustrated in Figure 3.7. Consider a coal burning power plant at X, which uses a fuel with a sulfur content that is such that it exactly meets the ambient standard; for example, in order to meet the maximum 24hr standard, coal with a sulfur content no higher than 0.8% might be used; the emission level is at A, the corresponding cost at K.

All other things equal, higher efficiency means some combination of lower costs and/or lower emissions. Suppose for example that the heat rate of the plant is improved; the production curve shifts from FF to GG, and the plant operates, say, at Z, where less fuel is required per kwh produced, so fuel consumption, and SO_2 emissions decrease; and the net cost to the utility goes down (fuel costs less the amortized costs of the investment that produced the heat rate improvement). But now the utility has an incentive to move to Y: by buying cheaper fuel, with a higher sulfur content further savings can be achieved without violating the standard, with the result that there is no environmental benefit, but only lower costs. Of course from the environmental perspective, the desired response would be to point W: here the savings from better heat rates would be applied to the purchase of still lower sulfur coal, say 0.7% sulfur by weight.

In Sri Lanka, where there is no large inventory of old, inefficient thermal plants (as exists, say in India), the most important system efficiency issue is T&D losses. As can be seen from Table 3.3, the progress in reducing losses to the present 12% target set by CEB has been much slower than anticipated: as recently as 1989 it was projected that the 12% target would

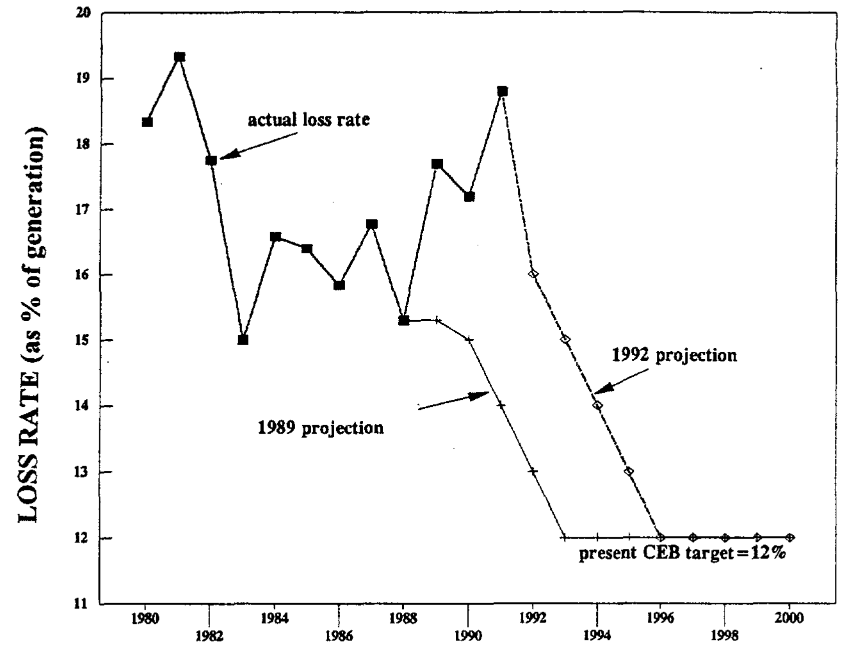


Figure 3.8: T&D loss projections (technical plus non-technical, as % of generation).

Table 3.3: T&D loss projections

year	actual	1989 projection	1992 projection
1980	18.3		
1981	19.3		
1982	17.7		
1983	14.9		
1984	16.5		
1985	16.4		
1986	15.8		
1987	16.8		
1988	15.3		
1989	17.7	15.3	
1990	17.2	15.0	
1991	18.8	14.0	
1992		13.0	16.0
1993		12.0	15.0
1994		12.0	14.0
1995		12.0	13.0
1996		12.0	12.0
1997		12.0	12.0
1998		12.0	12.0
1999		12.0	12.0
2000		12.0	12.0

be attained by 1993, yet by 1992 that target had been delayed to 1996. Given the lack of progress over the past few years (in 1991 losses actually increased), there is some question as to whether even this target can be attained.[12]

It is very important to recognize that technical T&D losses are proportional to the square of the load. This means that if T&D losses are specified in the conventional way as some percentage of total energy generated, this value cannot simply be applied across the entire load duration curve in a uniform manner. In other words, losses during the peak will be substantially higher than this average, and losses during the off-peak will be lower than the average. It therefore also follows that a reduction in average technical losses implies a much greater saving during the peak, and a somewhat lower saving during the off-peak.

However, one may note that reducing technical losses does not necessarily reduce demand. Since the power consumption in a purely resistive load is proportional to the square of the voltage, if T&D rehabilitation results in better reliability (fewer interruptions) and improved consumer voltages, demand may increase. However, in such a case, this demand increase is accompanied by increases in consumer benefits as well.[13]

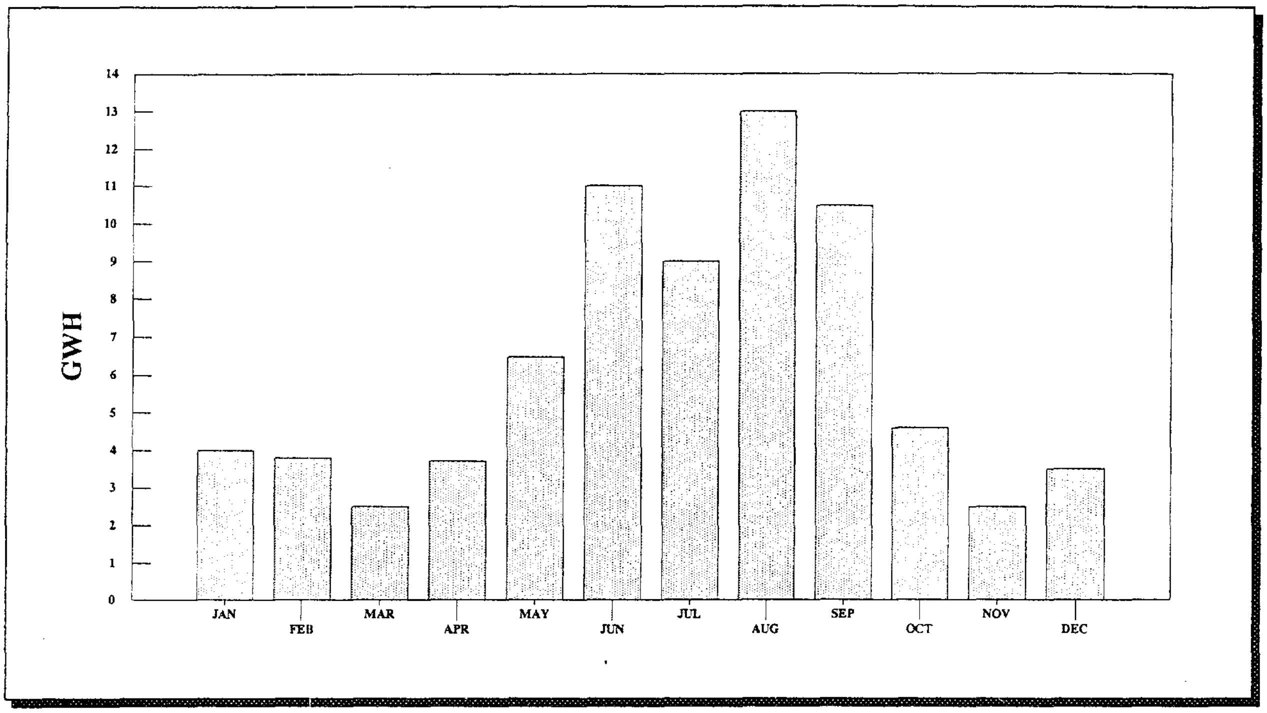


Figure 3.9: Monthly output for a 50Mw wind plant on the south coast

Renewable energy technologies: wind power plants.[14]

Although there are a number of renewable energy technologies that may be considered for Sri Lanka, the technology with the largest potential impact on the operations of the CEB is wind energy. Utility scale solar thermal plants appear to have little potential, while the use of photovoltaics probably has greatest potential in remote rural areas that do not have grid access. The extent to which it might actually be possible to displace one or more coal fired units with wind plants in Sri Lanka, and at what cost, is of obvious environmental interest.

Wind energy activities in Sri Lanka were started on a very modest scale as far back as 1978. Early activities were focused on the development of small wind pumps mainly for application in the agricultural sector for small scale irrigation during the dry season. At least one small scale workshop is now engaged in the commercial scale production of these machines.

A preliminary assessment of Sri Lanka's wind resources, using past meteorological data, identified the southern coastal region as one of the more promising areas for wind power development. A more detailed study of wind energy resources in the southern region was initiated in early 1988, funded by the government of the Netherlands.

This study indicated that the area from Hambantota towards Palatupana on the south-east offers the highest potential for wind power generation. Specific electrical outputs of about 800-900 $Kwh/m^2/year$ and plant factors of about 20% have been estimated for this region. The wind power potential within the five kilometer wide stretch of coastal land between Hambantota and Palatupana has been estimated as 300 Mw. The estimate is based on a power density of 8 Mw/km^2 and a 50% land utilization factor after excluding forest cover, agricultural land, homesteads and the Bundala bird sanctuary.[15] The effective area available for consideration is the region bound by the shoreline from Bundala to Palatupana, and extending inland to some 5-6 km, where the coastal wind regime still persists, though slightly reduced in strength. The coast line of this region lies at a distance varying from about four to six km from the main trunk road, from where there are several motorable roads heading towards the coast. There are no rivers flowing

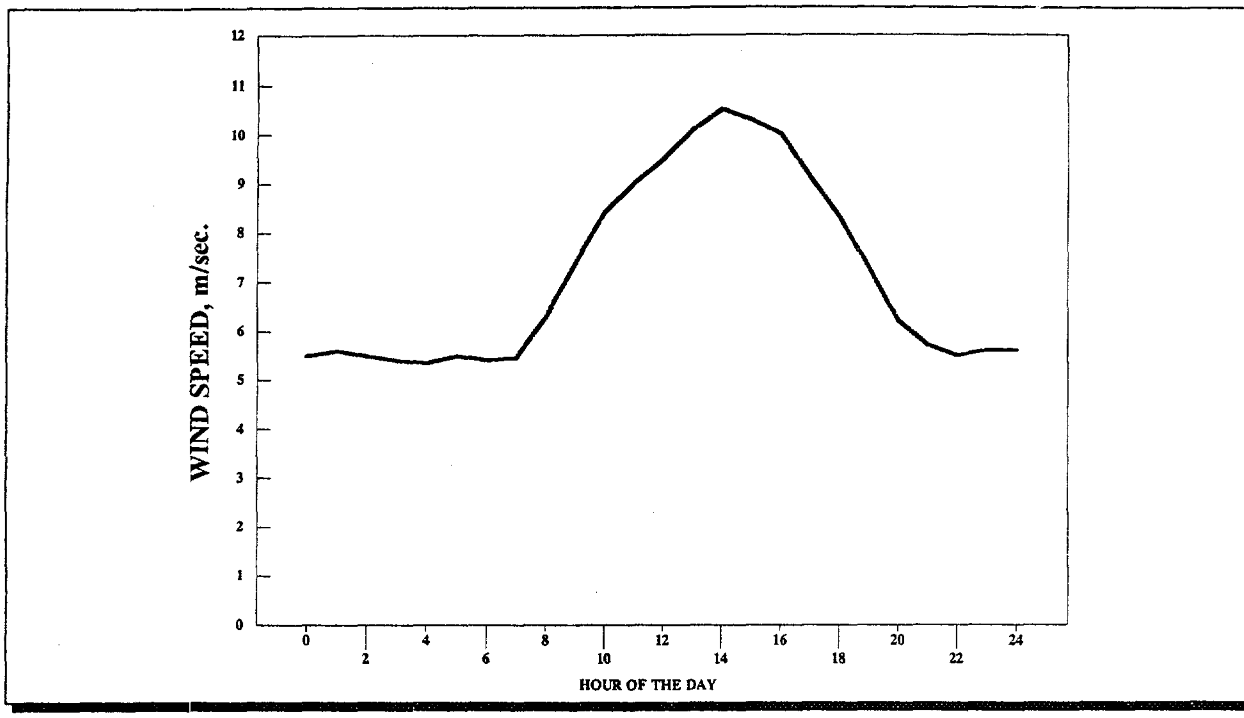


Figure 3.10: Hourly variation in wind speed

across this region, but during the rainy season, some of the low lying sandy areas are transformed into shallow water bodies, perhaps not exceeding two meters in depth. The development of wind energy in this region would not require significant investment in the improvement of general infrastructure, except for some minor roads leading to the candidate site.

As indicated on Figure 3.9, the monthly variations in energy generation are substantial, with peak generation during the summer months of the SW monsoon. The daily variations are equally important: as indicated on Figure 3.10, wind speeds are highest in the afternoon hours. However, the annual variations are relatively small, with a standard deviation of only 10% of the mean over the past thirty years. In particular there is little correlation between average wind speeds and drought conditions: in the severe drought year of 1983, wind generation would have been 10% above the long-term average. Detailed system studies indicate that there is little capacity benefit,and in normal to wet hydro years, wind energy serves primarily to displace thermal energy. In drought years, however, wind energy also serves to offset generation deficits.

Pollution control policy: FGD systems and clean coal technology.

The air quality modelling results conducted at Trincomalee for the EIS demonstrate without much doubt that if imported Australian coal is used, that typically has less than 1% sulfur by weight, then ambient SO_2 standards that are similar to those presently in use in the industrialized countries can be met without difficulty even when the full 900Mw envisaged for the site is fully developed. Nevertheless, the question of whether or not FGD is to be fitted to large coal-fired power plants is currently under intense debate in a number of developing countries, and FGD is certainly a potential option in Sri Lanka.

However, the shortcomings of conventional approaches to deal with the air pollution impacts of coal plants have long been recognized: rather than fix individual emission problems separately -- SO_2 control by FGD systems, NO_x control by burner modifications -- a much better approach is to use fundamentally different combustion

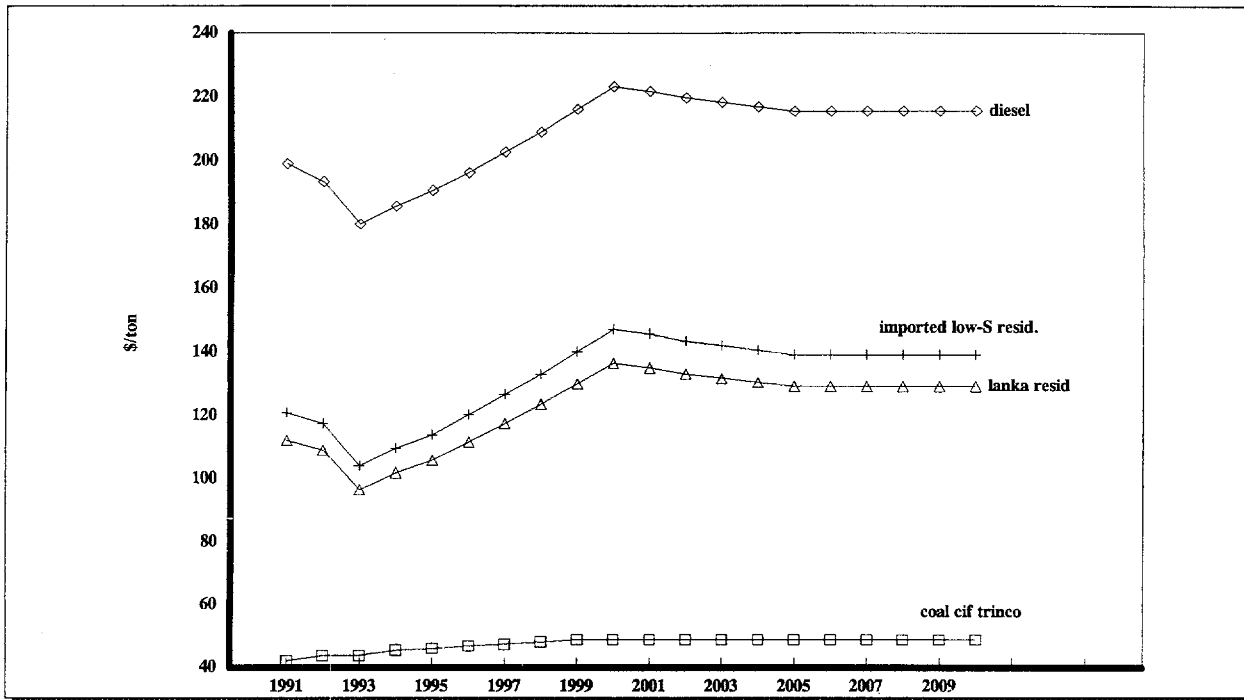


Figure 3.11: Fuel price projections in the 1991 CEB generation plan study. (In constant 1992$)

technologies. Over the past decade a substantial research effort has therefore been mounted into so-called clean coal technologies, including such technologies as atmospheric and pressurized fluidized bed combustion (AFBC, PFBC) and integrated gasification combined cycle (IGCC). A number of these are at or very close to commercial availability at the utility scale in the industrialized countries, and have lately been proposed for application in developing countries as well. In India, for example, IGCC is viewed as an attractive way of dealing with very high ash coals, and in Pakistan, fluidized bed combustion is under consideration as a way of dealing with the high sulfur contents of the Lakhra coals.[16]

In this study, therefore, for the purpose of examining the potential environmental benefits of such new technologies (especially vis-a-vis FGD), we hypothesize the general commercial availability of PFBC technology by the end of the 1990s, in combination with the use of a topping cycle.[17] Even though oil fired combined cycle plants, as examined in the CEB's 1991 generation planning study, have been found to be uneconomic, this is largely a consequence of high oil costs. But if coal can be used to drive a combined cycle plant, the inherently higher efficiency of such units is a major advantage where coal must be imported, and where freight costs may account for as much as one third of the delivered price.

The specific assumption here is that PFBC-CC units would be used for the third and fourth coal units to be built in Sri Lanka, but not for the first two units, presently planned for the Trincomalee site (possibly as a private power project). With the earliest possible start-up for the first coal unit estimated by the CEB to be 2001, with a six year lead time the technology commitment would need to be made by 1995, which would certainly be very optimistic. But with the first 300Mw unit projected for 2004, with a 1998 commitment date, that does not seem overly unrealistic as a date for successful commercial demonstration of PFBC.[18]

Fuel prices and fuel supply policy

Fuel price projections are obviously of critical importance, because they are a critical factor in determining the generation mix. This study used as a base case the September 1991 fuel

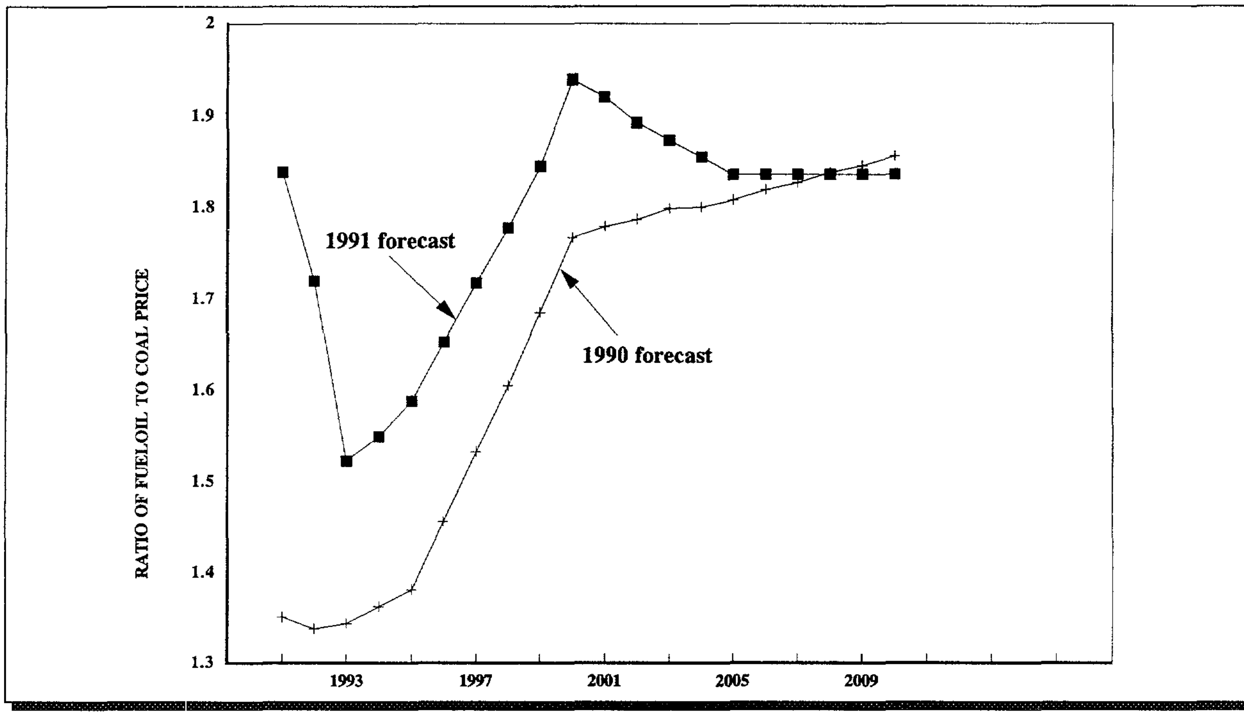


Figure 3.12: Projected ratio of fueloil to coal price (adjusted for energy content)

price projections of the CEB, as illustrated on Figure 3.11.

However, is not just the absolute level of prices that matters, but for Sri Lanka a critical variable is the ratio of coal to heavy fueloil price, because it is this ratio that determines the balance of diesel and coal plants in the generation mix, in turn of central importance to the environmental impacts that follow. The projected relative ratio of fuel oil to coal price is shown on Figure 3.12. One observes substantial differences between the relative prices projected in 1990 and 1991, particularly for the 1990s. In part this is attributable to the impact of the 1990/91 Gulf Crisis, which resulted in an upward revision of the 1991 oil price projections, but had relatively little impact on the corresponding coal price projection.

Historically the ratio of fueloil to coal price has shown great fluctuations: by late 1984 this ratio stood at 3, a sure indication that crude oil was over-priced. As the price of crude (and heavy fueloil) fell sharply in the mid-eighties, the fueloil to coal price ratio also fell, reaching less than one in early 1986. Indeed, this was a time when many dual-fueled plants, that had been converted from oil to coal in the late 1970s, switched back to residual oil.[19]

Based on this historical perspective, the long term equilibrium value of about 1.85 suggested by the World Bank-based projections seems somewhat high, since it parallels the market conditions of the early 1980s, and again of late 1985.

In addition to the question of the relative price of coal and fueloil, also of interest to this study is the relationship between price and sulfur content: as we shall see later, the use of higher-cost, lower sulfur fuels proves to be cost-effective when compared to other pollution mitigation options (and particularly when compared to the use of flue-gas desulfurization systems). The premium between 3.5% sulfur heavy fuel oil, and low sulfur, 0.5% oil on the Singapore spot markets has been about $4/bbl over the past five years.

Table 3.4: Policy options examined in this study

policy emphasis	illustrative measure
demand side management	fluorescent lighting
system efficiency	T&D loss reduction
supply side options	no coal
	acceleration of various hydro plants
renewable energy technology	wind power
fuel supply strategy	imported low sulfur fueloil
	low sulfur coal
pollution control policy	FGD systems
clean coal technology	pressurized fluidized bed combustion (PFBC).

Study scenarios

Table 3.4 summarizes the various options that are examined in this study, and for which we wish to demonstrate the environmental trade-offs. Obviously most of these are not mutually exclusive, and combinations of the various options may be desirable.

Moreover, in some cases there is a strong interaction between measures when they are combined. Given the very large number of combinations that are possible (particularly when the question of timing is also considered), the approach taken is to first perturb the basecase (namely the 1991 CEB expansion plan) for each of these options one at a time, and then in a second stage examine combined strategies of only the most favorable options.

Notes

[1] Although during the initial period from 1986 to 1987 Trincomalee was easily accessible through road or air, due to civil disturbances during the latter part of the 1980s, it became more and more difficult to reach Trincomalee. During this period, the main 132 Kv power lines to Trincomalee were disrupted several times by terrorists. Road transportation became risky. The Consultants, and others, who had to visit Trincomalee for purposes of study had to rely mainly on air transportation.

[2] Black and Veatch International, *Trincomalee Thermal Power Project, Site Evaluation and Selection Study, Phase II, Final Report*, Ceylon Electricity Board, Colombo, Sri Lanka, September 1985.

[3] In 1993 a Canadian developer put forth a proposal to develop the Trincomalee site for a 2 x 150Mw as a private sector operation. It remains to be seen whether the security situation has improved sufficiently for the power evacuation issue to be satisfactorily resolved.

[4] Black and Veatch International, *Thermal Generation Options Study*, Report to the Ceylon Electricity Board, Colombo, Sri Lanka, October 1988.

[5] Reliability reasons dictate that the largest single unit ought normally to account for no more than 10% of the peak load.

[6] The definition of "average" hydro conditions, as used in the 1991 CEB system planning studies, is the weighted average of three specific hydro conditions: a 1 in 10 year ("very dry"), a 2 in 10 year ("dry"), and a 7 in 10 year ("medium") case. For example, the SYSIM model results for 1994, for the existing hydro plants and Samanalawewa, are as follows: the total average hydro of 3869 gwh corresponds to the number on Table 3.2.

	medium	dry	very dry	weighted average
dispatched hydro	3984	3314	2812	3736
hydro spill	174	56	0	133
total hydro energy	4158	3370	2812	3869

[7] Such assessments have recently been conducted for India (as part of a recent World bank/USAID power sector review) and Costa Rica (see *Costa Rica Power Sector Efficiency Assessment*, Office of Energy, USAID, Washington, DC, July 1983.

[8] *Sri Lanka Power System Loss Reduction Study*, UNDP/World Bank Energy Sector Management Program, Report 007/83, July 1983.

[9] The World Bank study also examined the possibility of replacing self-ballasting mercury vapor and incandescent lamps used for street lighting by high pressure sodium vapor bulbs.

[10] However, the methodology developed here would be directly applicable to any future environmental assessment of railway electrification.

[11] A study in Haiti indicated that kwh consumption returned to between 45% and 50% of consumption formerly obtained by theft. See W. Hay, Power loss reduction may not be an effective tool for demand management, ESMAP Connection, Vol. 1, 2, p.11 (Oct 1992).

[12] In fact, actual loss rates are likely to be somewhat higher, since CEB treats HT sales to local authorities and to LECO (a privatized, though still government owned distribution company) as end-use consumers. LECO was formed in 1983 to take over the distribution systems of a number of municipal authorities that had extremely high loss rates, in some cases over 40% at the time of takeover. Over the past decade LECO has largely rebuilt the distribution system in these areas with loan assistance from the Asian Development Bank, and coupled with an aggressive policy of disconnection in response to non-payment of bills, has managed to bring down its loss rate to less than 10%.

[13] For further discussion of this point, see e.g. Hay, *op. cit.*

[14] This section reflects the significant contributions of Mr. Sumith Fernando, the project coordinator of the Wind Power Study. We draw also, in parts verbatim, on his report "Proposal for establishment of a grid-connected pilot scale wind power plant", Ministry of Power and Energy, November 1991.

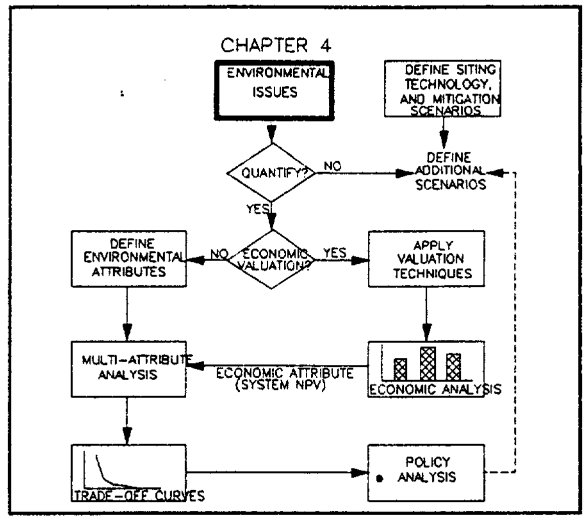
[15] The western part of this area has long ago been declared a bird sanctuary which is considered the habitat for numerous species of migratory birds. There is some evidence that wind farms do indeed pose dangers for birds: at the Altamount wind farm in California, some 200 raptors have died every year, and thus the exclusion of the Bundala sanctuary seems indicated.

[16] For a history of the Lakhra project in Pakistan, see e.g. T. Wilbanks, Implementing environmentally sound power sector strategies in developing countries, Annual Review of Energy, 15, pp. 255-76, 1990. Lakhra coal has a very high sulfur content (in the range of 6.8-9.3% by weight, certainly much higher than other coals found on the Indian subcontinent). Initially tall stacks were proposed as a compliance measure, then the size of the project was scaled down, then FGD systems were proposed, and then, finally, FBC was chosen as the most appropriate technology.

[17] There are four utility scale demonstration plants presently at or very close to commercial operation: a 200Mw unit at Tidd, Ohio; the 330Mw Philip Sporn plant in West Virginia; a 200mw plant at Escovar, Spain, which will burn black Lignite that has 6.8% sulfur, 20% moisture and 36% ash; and a 135Mw plant in Stockholm, which is configured not as a combined cycle but to also produce 225Mw (thermal) of steam for district heating.

[18] The objection has been raised by some that PFBC-CC is a very sophisticated technology that may be beyond the capabilities of the CEB to operate and maintain successfully. However, the same argument could be made for even concentional pulverized coal technology fitted with FGD, for which the CEB also has no operating experience. However, if coal plants are going to be developed by the private sector, involving overseas consortia, there seems no reason why PFBC technology could not be used. Indeed, Asea Brown Boveri, one of the leaders in this technology, has shown very strong interest in private sector projects in South Asia.

[19] One might note that some dual-fuel capable plants did *not* switch back to oil during these periods when heavy fuel oil was cheaper on a Btu basis at the burner tip, largely because of distortions in the domestic fuel pricing system. For example the dual-fuel plants at Mohammedia in Morocco stayed with coal throughout this period because the Government left the domestic fueloil price at the 1981 level (capturing the windfall for itself as an excess profits tax on the domestic refineries).



4. ENVIRONMENTAL ISSUES

We turn next to a presentation of the environmental issues that need to be considered by the power system planner in Sri Lanka. Because hydro-electricity dominates the present power system, it is hardly surprising that the principal environmental issue that the power sector has had to deal with in the past has been the relocation and resettlement of people displaced by reservoirs[1].

In recent years, the few thermal plants in the system (the diesels at Sapugaskanda, and the combustion turbines and steam plant at Kelanitissa) have been only sporadically operated, and neither facility is seen to have major environmental problems.[2] But as the system gradually shifts towards a greater role for thermal plants, the major issues will also shift towards those associated with such plants. Clearly, these are of a quite different nature to those at hydro plants, and indeed how to compare the two types of quite different impacts -- primarily air and thermal discharge issues at thermal plants, against land use issues at hydro plants -- is one of the main themes of this case study.

The comments received in response to the Trincomalee EIS is a good indicator of what these new concerns are likely to be. As required by regulations, this document was circulated for public comment, and on Figure 4.1 we illustrate

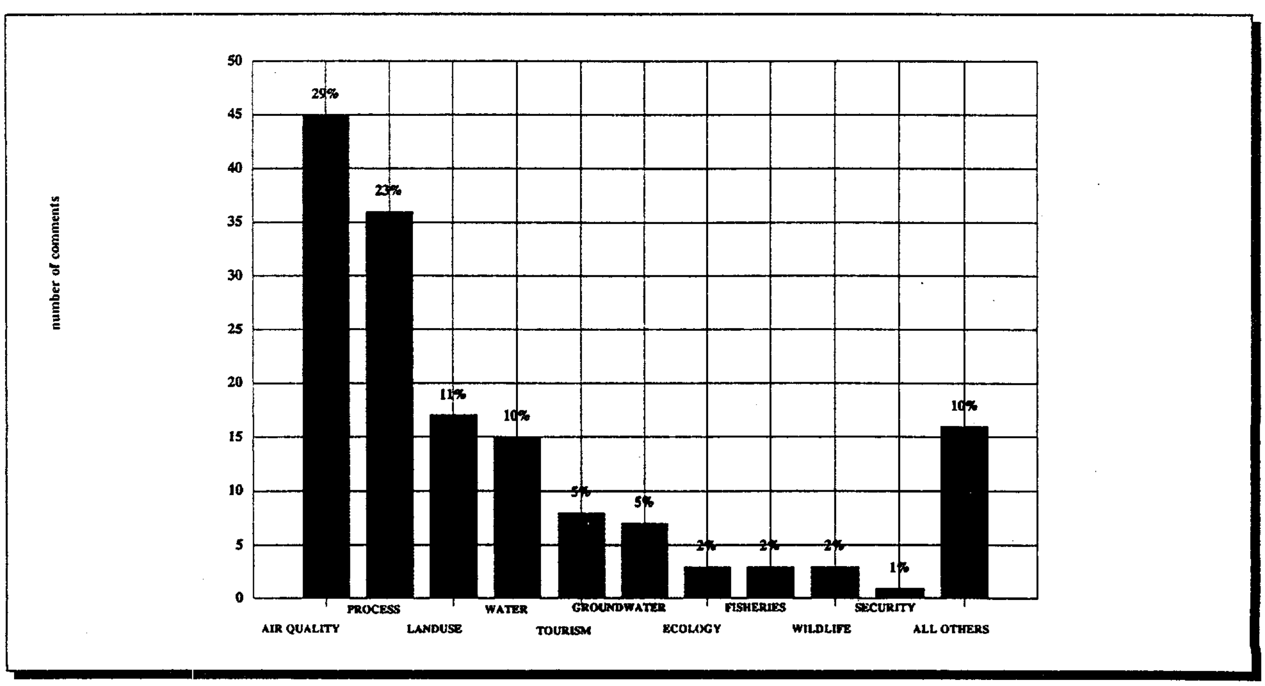


Figure 4.1: Public comments to the Trincomalee EIS.

Table 4.1: Environmental Issues at the Samanalawewa Hydro Project
(as raised by the 1990 ODA assessment of the project)

construction phase issues
water table drawdown during power tunnel construction
removal of biomass from the area to become inundated
need to ensure adequate irrigation water supply immediately downstream of the reservoir for a 2000 acre rice paddy irrigation scheme (and the possible need for compensatory water supply).
resettlement issues: (1) need to extend attention from families with property to landless laborers, tenants and traders whose customers move from the area. (2) need to establish more formal counseling service arrangements.
archeology: a preliminary assessment discovered some unique iron smelting sites dating to the 6-9th centuries AD; ODA recommended a complete excavation of the site prior to inundation.
long term issue
need for an environmental management plan (for both upstream and downstream areas)

Source: Overseas Development Administration (ODA), *Social and Environmental Issues at the Samanalawewa Hydro Electric Project*, February 1990.

the results of an analysis of the 154 comments received. That air quality would be the major concern at a coal fired plant is to be expected: but the second most frequent concern was over the process by which a coal-fired power plant had been selected for this particular site. As noted earlier, widespread dissatisfaction was expressed by NGOs and others over the way in which decisions had been reached.

Land use and resettlement impacts at hydro plants

The recently completed Samanalawewa hydroelectric project, illustrates well the kind of environmental issues associated with hydro development in Sri Lanka. An earlier Overseas Development Administration (ODA) evaluation of the Victoria project highlighted a number of social and environmental issues, and several ODA missions were undertaken during construction of the Samanalawewa project to ensure implementation of mitigation measures. Table 4.1 summarizes the issues addressed in their 1990 report[3].

Sri Lanka is one of the more densely populated countries of the world, and land availability to support a growing population is an important issue. In general, hydro sites are in the wet zone areas where there is little available land nearby for resettled inhabitants to be re-located: and such land as is available at greater distances (mainly in the newly irrigated dry zone areas of the Mahaweli schemes) is often seen by potential evacuees as undesirable because of questions concerning the availability of adequate water supply.

A crude, but relatively effective way of comparing the likely extent of potential land-related environmental impacts across projects is the area inundated per Kw of capacity; as indicated on Figure 4.2, this varies from essentially zero to as high as 150 ha/Kw. More importantly, the correlation between the installed capacity of a project and the amount of land to be inundated is poor; this simply implies that large projects do not necessarily mean worse environmental impacts, and vice-versa.

Figure 4.3 illustrates this relationship in terms of average energy rather than installed capacity of hydro projects. Because the plant factors are all very much in the same range (mostly between 0.35 and 0.45), there is no significant difference in the relationships between installed capacity and area, and energy and area.

Another useful indicator of potential impact is the population affected: on Figure 4.4 we show the estimated population to be resettled per Mw as a function of the size of project; again the correlation is seen to be quite poor.

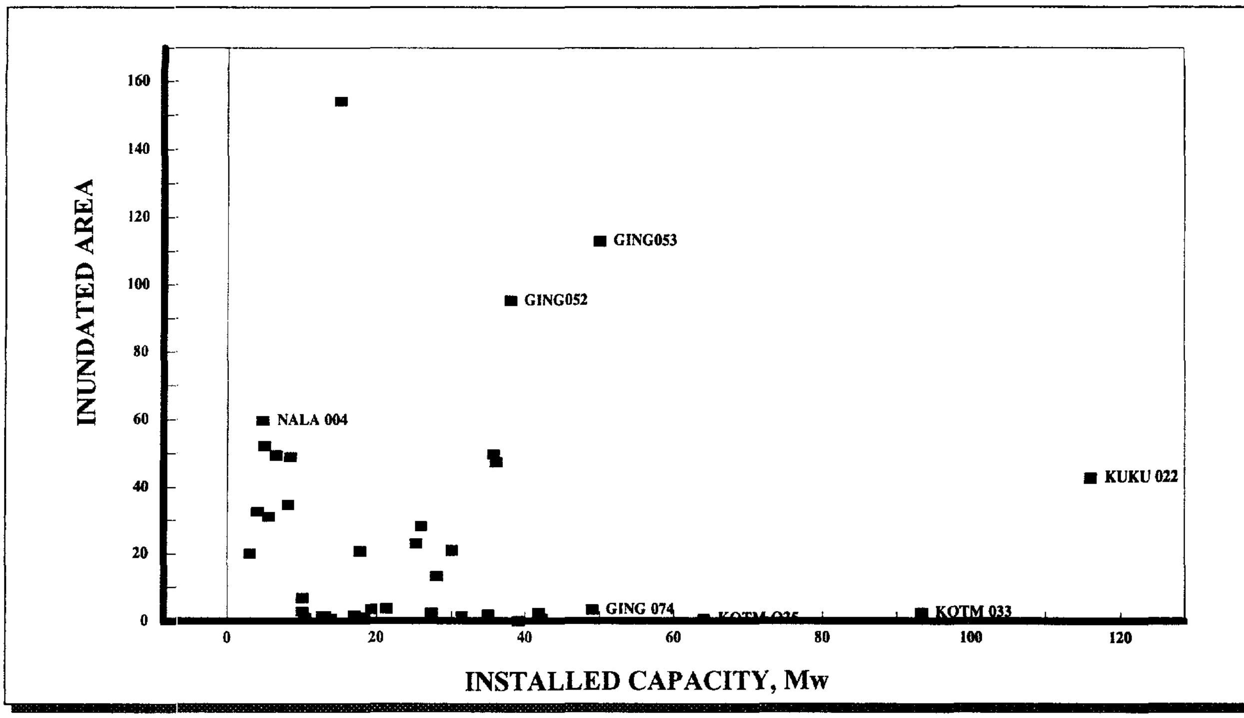


Figure 4.2: Relationship between installed capacity of potential hydro projects and area inundated

On the basis of the recent experience at Samanalawewa, where some new ideas have been tried by the CEB, the resettlement issues at most of the remaining major hydro sites appear to be tractable. At Samanalawewa itself, as of the time of writing, the families from the power station site have already been moved an resettled in a tea estate, and some 365 families remain to be re-settled. Of these, 68 have agreed to move to the Mahaweli area, 80 are still negotiating,

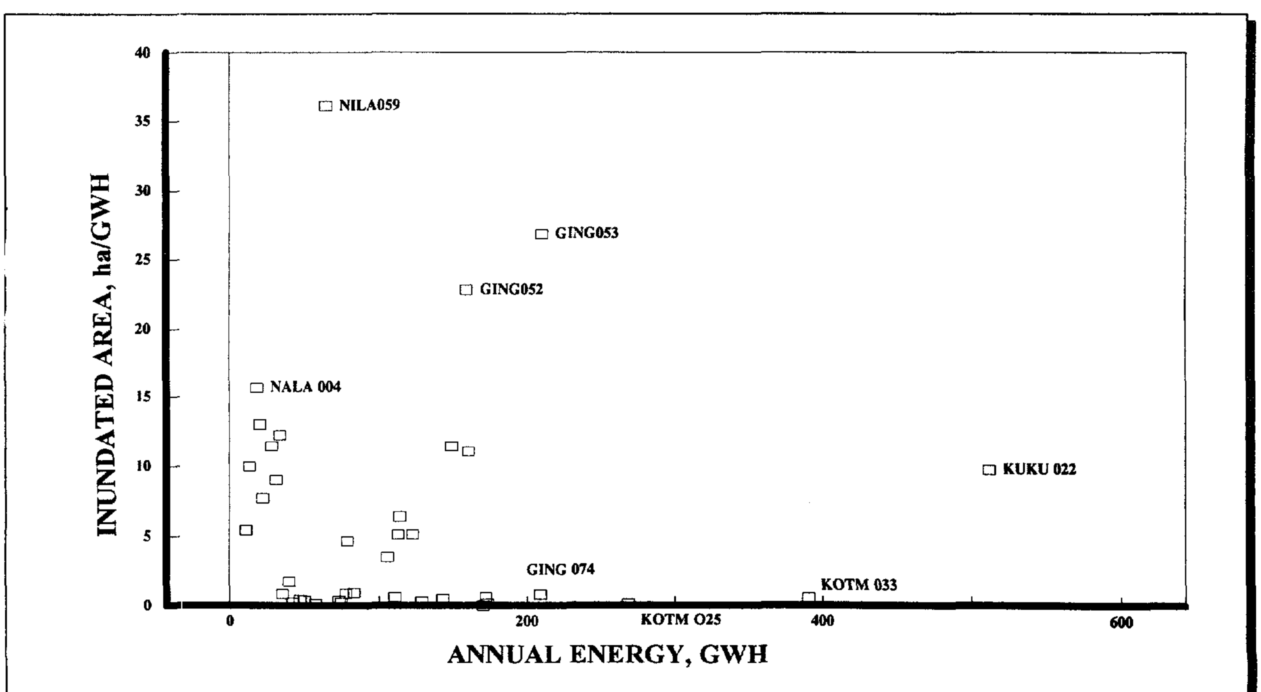


Figure 4.3: Relationship between hydro energy and area inundated.

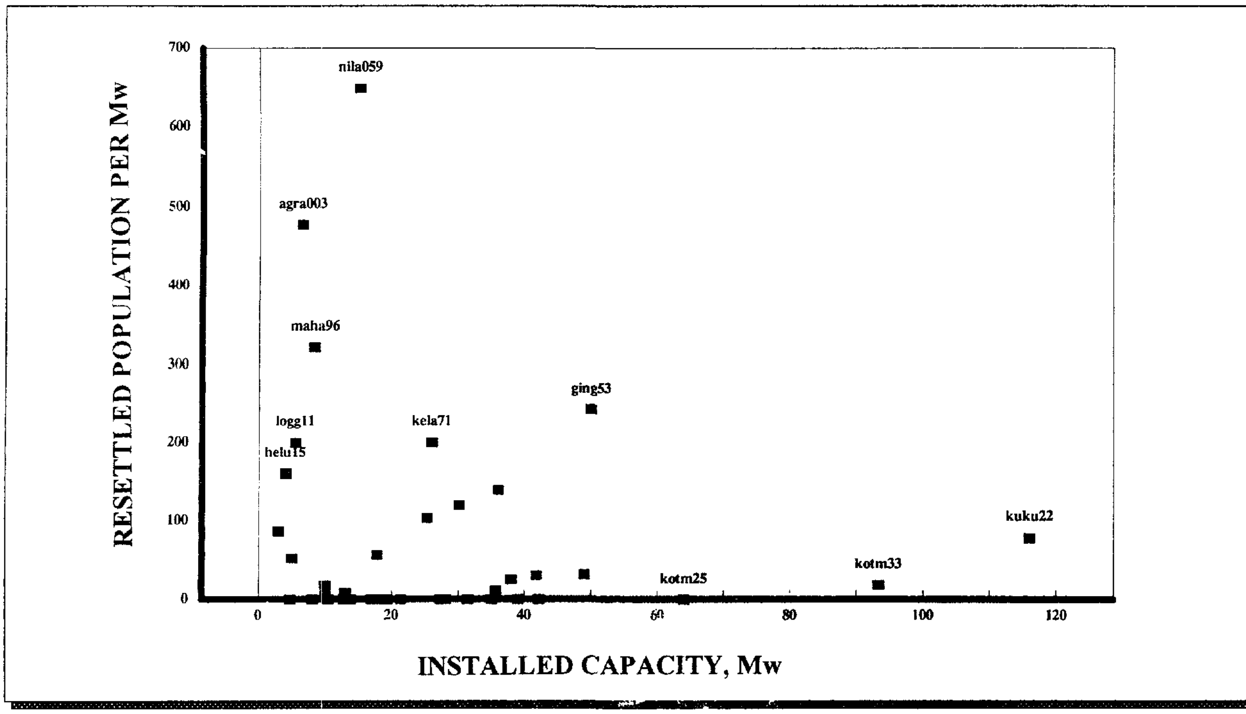


Figure 4.4: Population displaced per Mw

Table 4.2: Main characteristics of the remaining hydro sites in Sri Lanka

name of project	GTZ code	surface area at FSL, Km^2	Mw	resettlement
Madula Oya	MADU 003	0.6	72	0
Upper Kotmale	KOTM 025	0.4	64.4	0
Broadlands	KELA 085	v. small	38.8	0
Moragolla	MAHW 263	0.7	27.3	0
Kukule	TAMS/high dam	20.8	144	9,500
Ging Ganga	GIGN 053	56.4	49	12,150
Upper Uma Oya	UMAO 034	0.3	42	0
Ging Ganga (Bentota)	FINF 052	36.2	38	11,750
Kotmale Oya (Talawakele)	KOTM 033	2.3	93.3	1,710
Uma Oya (Rantabe)	UMAO 008	0.7	35	0
Uma Oya (Bathmedilla)	UMAO 021	0.4	31.4	0
Uma Oya (below Welimale town)	UMAO 042	1.1	41.8	1,210
Uma Oya (Diyabola Vil Badulla)	UMAO 034	0.2	42.1	0

and 120 have agreed to find on their own land for resettlement in return for an additional cash payment. This has the merit that evacuees are given the opportunity to resettle in areas of their choice, and reduces the pressure of meeting the demands of evacuees by government organizations.

It might be noted that in comparison to hydro schemes in other countries, the amount of land inundated per installed Mw is rather modest, as indicated on Table 4.3.

The one major hydro project where substantial resettlement issues are likely to occur in the future is at Kukule. Although there are a number of variants of this project currently under study, the 144Mw GTZ Masterplan variant of the Kukule project, which at 2080ha has the largest reservoir size of any of the remaining hydro projects, estimated that some 9100 persons would need to be evacuated. This represents four times the number of potential evacuees as at Samanalawewa, and will therefore require very careful management.[4]

On the other hand it should be noted that this Kukule project variant will also provide substantial irrigation benefits. The Masterplan Kukule variant calls for some 68,000ha to be irrigated in the southeastern dry zone, of which some 95% would be new land. The net increase in agricultural production would substantially offset the production losses in the area affected by reservoir inundation, and would provide substantial employment in an area of high youth unemployment.

A comprehensive feasibility study of the Kukule project has recently been completed, and the now recommended option is a 70Mw run-of-river project that involves the resettlement of only some 27 families. In this report we refer to this option as the "Kukule run-of-river" option, as opposed to the larger, 144Mw "Kukule high dam" option that was used by the CEB in its 1991 generation planning study. A feasibility study of the Upper Kotmale project, whose upper reservoir would also require substantial resettlement, is currently underway.

Other impacts at hydro sites

Most hydro plants in the hill country of Sri Lanka involve power tunnel diversions, typically leaving 5-10km distances immediately downstream of the dam with minimal flows. There is some speculation that stagnant water pools downstream of the Kotmale dam have played a role in the resurgence of Malaria in the area[5]. Certainly one can observe mosquitoes breeding in the potholes downstream of the dam, and downstream releases may need to be

Table 4.3: International Comparisons, area inundated per kW.

	km^2 inundated	mW	km^2/mW
Sri Lanka			
Kukule (TAMS)	20.8	144	0.14
Ging Ganga (GIN052)	1.7	49	0.34
Elsewhere			
Balbina, Brazil(1)	2360	250	9.4
Narmada Sugar, India	913	1000	0.9
Akosombo, Ghana	8482	833	10
Cabora Bossa, Mozambique	3800	4000	.9
Grand Coulee, United States	324	2025	.16
Itaipu, Brazil & Paraguay	1350	12600	.11
LaGrande 1, James Bay, Canada(2)	40	1368	.03
LaGrande 2, James Bay, Canada(2)	2630	5328	.49

source: (1) P. Fearnside, Brazil's Balbina Dam: Environment versus the legacy of the Pharaohs in Amazonia, Environmental Management, 13,4,p.401-423 (1989); (2) F. Berkes, The Intrinsic Difficulty of Predicting Impacts: Lessons from the James Bay Hydro Project, Environmental Impact Assessment Review, 8,201-222 (1988); Sri Lanka projects from the GTZ Masterplan Study.

increased. However studies of how much water would need to be released to eliminate such breeding grounds, and whether in fact these breeding grounds represent a significant fraction of mosquito breeding grounds in the area, have yet to be done. Moreover, even before the impoundment, parts of the river bed dried up during the dry season.

A further reason for requiring minimal flows downstream of some dams is the potential elimination of scenic waterfalls. For example, the St.Clair falls, downstream of Talawakelle, would be eliminated by the proposed upper Kotmale hydro project (that involves two dams, one at Caledonia, and a run-of-river downstream at Talawakelle).[6]

Water quality problems in impoundments that provide seasonal storage may be quite severe, as illustrated by the recent problems encountered at the Kotmale reservoir. Because of the high use of fertilizer in the watershed areas, particularly in tea lands, algal blooms have become a serious problem at Kotmale.[7]

Finally, there has been much discussion of the relationship between impoundments and landslides in the Sri Lanka hill country. However, the study by Johansson[8] of the Kotmale area, where hundreds of houses have experienced cracks and foundation problems, shows there is no scientific evidence that the existence or operation of the reservoir has caused mass movements and soil creep. Indeed, according to Johansson, "..oral written evidence shows that major mass movement events took place in 1933, 1947, 1957, 1958, 1970 and 1979", i.e. before the impoundment.

Deforestation

The progressive loss of Sri Lanka's natural forest over the past 50 years is well documented, and represents one of the country's most important environmental concerns. Power sector projects will likely be scrutinized very carefully for their potential impact on what natural forest areas remain, even if it is true that the power sector per se has been a relatively minor contributor to the loss of forest lands. The main reasons for deforestation in the past have been planned agricultural development and settlement schemes, chena cultivation, encroachment by unplanned settlement and cropping, illicit logging, and uncontrolled fuel wood and timber extraction.

Air quality

Relatively little is known about ambient air quality in Sri Lanka, except perhaps on a very general level: in most parts of the country the air quality is good, a reflection of the limited extent of industrialization (except in Colombo), and the natural ventilation provided by strong monsoonal wind regimes. In Colombo, however, the sharp increase in automobile and bus traffic over the past decade has led to a deterioration of urban air quality. Between 1970 and 1990 the number of vehicles registered annually in Colombo has increased fourteen-fold. It is estimated that vehicles produce 98% of carbon monoxide emissions, 79% of NO_x, and 46% of SO_2.[9] With 60% of the country's vehicles registered in the Colombo area, and with about 60% of the total industry, the outlook for air quality in Colombo, while still nowhere close to the levels experienced in other Southeast Asian cities, will become increasingly poor in the absence of appropriate actions.[10]

The first major effort to monitor air quality began in 1989 when the National Building Research Organization (NBRO) initiated a three-year program for monitoring air quality in Colombo; in a first phase, a city-wide survey of dustfall and sulfation rates is being conducted, with detailed measurements of SO_2, particulates and NO_x to follow in phase two for those areas with unsatisfactory air quality.

This program is viewed as a necessary first step not just to develop a database for Colombo, but also to assist in the formulation of national air quality standards, and to establish a permanent capability. Nevertheless, based upon what we do know about patterns of energy utilization, certain inferences can be drawn. It is fairly certain that at present the power sector contributes only marginally to air pollution in Sri Lanka. At the moment, the existing thermal plants in and around Colombo presently need not be run at all during a normal hydro year. However, once the anticipated coal burning

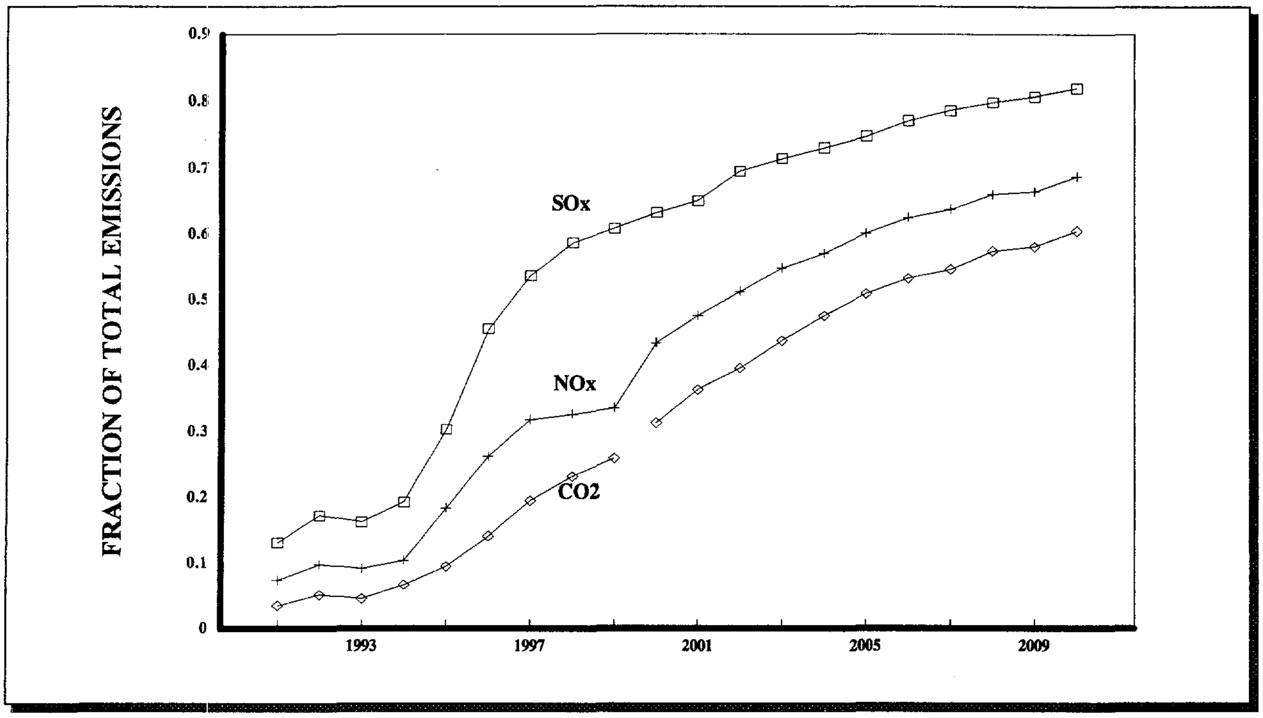


Figure 4.5: Estimated contribution of the power sector to air pollutant emissions in Sri Lanka.
(based on the base case CEB expansion plan of September 1990.)

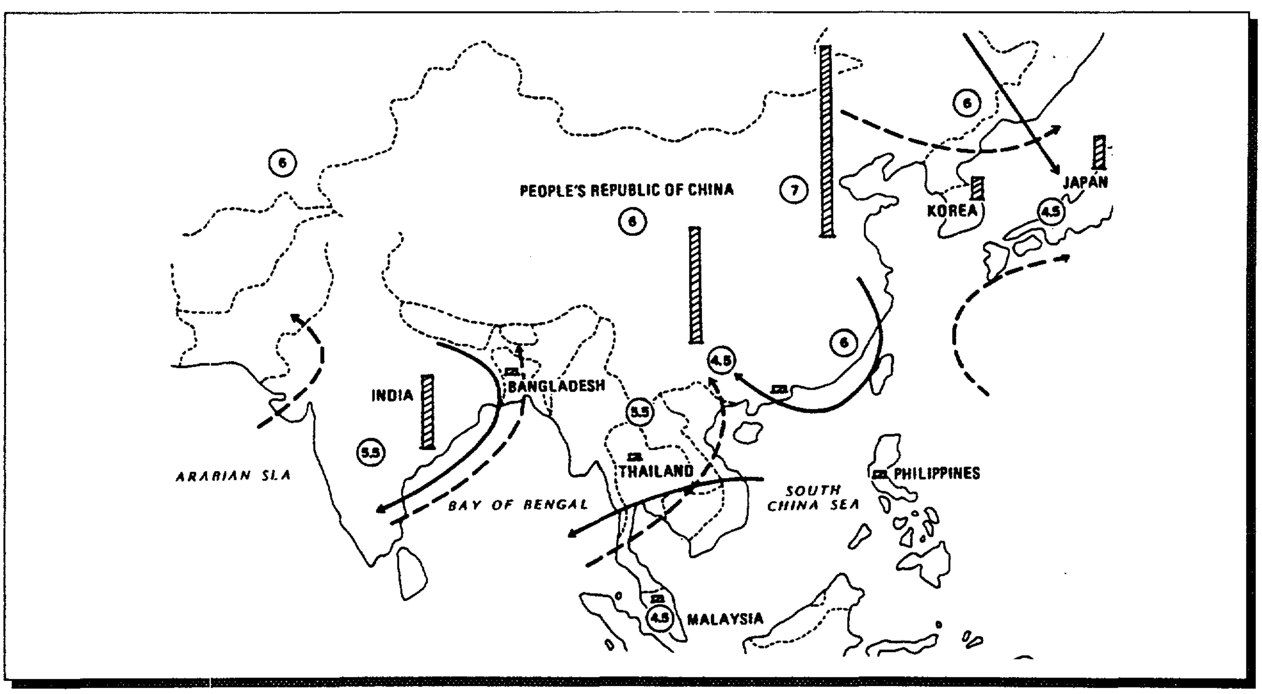


Figure 4.6: Elements of the Acid Rain Situation in Asia
(Source: W. K. Foell and C. Green, 1990)

power plants are added to the system beginning in the late 1990s, this is expected to change significantly; as illustrated on Figure 4.5, from essentially zero in 1991, the power sector is expected to contribute 80% of SO_2 and 70% of NO_x emissions by 2010. Clearly the potential for significant degradation of air quality is the major environmental concern associated with coal burning power plants. The options to minimize such air pollution impacts, whether by technology choices -- say by application of some of the newer clean coal technologies such as fluidized bed combustion (FBC), by impact mitigation options such as by the use of flue gas desulfurization system (FGD), or by locational choices -- is one of the main themes of this report. Another major uncertainty is the air quality impact of the use of traditional fuels, particularly in the congested lower income areas of Colombo where fuelwood and agricultural wastes are still widely used as a cooking fuel.

Acid Rain

Acid rain is likely to become an increasingly important environmental issue in the Asia-Pacific region given the fact that the energy plans in many countries, and India and China in particular, call for rapid development of fossil energy systems. Acid rain is largely a long-range phenomenon, and it is fairly obvious that the extent to which acid rain is or will be experienced in Sri Lanka is as much a function of emission trends of acid rain precursors (SO_2 and NO_x) in India as in Sri Lanka itself. As suggested by the predominant wind directions in South Asia (see Figure 4.6), the most significant source of acid rain precursors to Sri Lanka would be coal-burning power plants on the East coast of India.

In light of these observations, it is clear that the debate over the potential acid rain consequences of the Trincomalee coal fired plant, as evidenced by the discussion in, and comments to the EIS, was not very well founded. Clearly what is most relevant are not SO_2 emissions in North America (which was used by the consultant as the yardstick of comparison), but emissions in India.

It is probably true that from a local acid rain perspective, the best location for a large coal burning power plant would be the south/southeast coast: since the plumes from this location would be overland for a much lesser distance than at either the Colombo or Trincomalee areas. However, different intensities of these two monsoons (winds averaging about 12km/hour during the northeast Monsoon, and 19km/hour in the Southwest) make even such simple comparisons quite uncertain. In any event, we know of no study of the potential impact of acid rain on crops and ecosystems in Sri Lanka, or of the buffering capacity of soils and water bodies.

Global Warming

Global warming (and transnational acid rain) are conceptually different from local environmental impacts, since in the former case the impacts will occur predominantly in other countries. If the main economic objective is to maximize welfare in Sri Lanka, decision-makers in Sri Lanka would be unwilling (and justifiably so) to incur additional costs (for example to reduce CO_2 emissions) if the benefits of such actions accrue mainly to other nations.

Our assumption in this case study assumes that Sri Lanka will be reimbursed by the international community for the incremental costs of global warming mitigation efforts, or that the Government would have signed an international agreement committing itself to undertake certain CO_2 emission reduction measures. In either event, power sector planners would need to consider the impact of alternative expansion strategies on greenhouse gas emissions.[11]

Carbon emissions in Sri Lanka, both in absolute terms as well as in per capita terms, are extremely low (see Table 4.4), a reflection of the dominance of hydro in the electric sector, and low energy intensity of the industrial sector. However, beyond the year 2010, CO_2 emissions will rise very sharply as the electric sector generation mix moves toward fossil fuel. This has important consequences for the negotiating posture of Sri Lanka in the event that a consensus emerges for tradable CO_2 emission

Table 4.4: Fossil Energy Carbon Emissions, 1986

Country	1986 emissions million tons carbon	tons carbon/ capita	tons carbon /$US1000 GNP
China	548	0.5	1.7
India	119	0.2	1.5
Indonesia	27	0.2	0.4
Thailand	12	0.1	0.3
USA	1418	4.9	0.3
Japan	268	2.0	0.1
U.K.	161	2.9	0.2
Sri Lanka	0.9	0.056	0.13

source: Sri Lanka estimates by the writers, others from W. Baron and P. Hills, *Greenhouse Gas Emissions; Issues and Possible Responses in Six Large Lower Income Asian Nations*, Working Paper #45, Center for Urban Planning and Environmental Management, University of Hong Kong, 1990.

rights; clearly it will be in the interests of small developing countries whose present electric systems are hydro dominated to argue that the initial allocation of emission rights be based on population, or income, rather than on present fossil fuel consumption.

Indeed, Sri Lanka may be an example of a country that may be as much affected by the global measures to reduce CO_2 emissions, as by the physical impacts of any global warming that may in fact occur. Some of the recent studies of measures that might be necessary to stabilize CO_2 emissions have staggering implications for developed and developing countries alike. At the June 1991 meeting of the Energy Modelling Forum, whose focus was the energy sector impacts of greenhouse gas emission control strategies, a number of models suggested that the level of carbon taxes necessary to stabilize emissions (typically defined as 1990 emission levels by 2005) should begin now at over $100 per ton of carbon, rising, in some cases, to as much as $550/ton by 2005.

Such tax levels are perhaps not very likely to materialize. Yet much more modest rates of carbon tax, even if imposed only in the industrialized countries, will have substantial implications for relative fuel prices. And as noted in Chapter 3, the ratio of coal to oil prices has particular relevance for fossil fuel importing countries such as Sri Lanka.

On the other hand, the impacts of global warming that might be experienced by Sri Lanka are also quite speculative. Some researchers expect an intensification of the monsoon in tropical latitudes, which may adversely affect soil erosion and stability in the hill country watersheds where deforestation rates have already increased sedimentation rates experienced by hydro and irrigation reservoirs. Unlike many other countries in Southeast Asia, tectonic conditions are relatively stable, with little significant seismic activity of the type that has produced significant surface depressions of coastal areas in the Philippines.[12] Nor are the major cities presently threatened by major subsidence problems caused by excessive exploitation of groundwater.[13] Nevertheless, extensive areas of the coast, especially in the south and southwest, are already threatened by coastal erosion (that can, at least in part, be attributed to large scale mining of coral reefs), and there are extensive areas of highly populated coastal areas that would be severely affected by sea level rises of 1-3 meters. In the North, one of the immediate consequences of sea level rise is likely to be contamination of the limestone aquifers that are important sources of groundwater for the north.

Whatever may be the resolution of these uncertainties, it seems clear that power sector planners, at the very least, will need to be much more aware of this debate than in the past, and should be cognizant of the implications of alternative expansion strategies on CO_2 emissions, especially in relation to any future global agreements on emissions and their financial and technical ramifications. We therefore include CO_2 emissions as one of the environmental factors to be considered in this study.

Biodiversity

Because Sri Lanka is a small island, which has been isolated for relatively long periods, there are a large number of endemic (unique) species (see Table 4.5). Among Asian countries, Sri

Table 4.5: Composition of Flora and Fauna

group	number of described species	percentage endemic species
FLORA		
algae	896	na
fungi	1920	na
lichens	110	35
mosses	575	na
liverworts	190	na
ferns	314	18
gymnosperms	1	0
angiosperms	3100	27
FAUNA		
land snails	266	na
spiders	400	na
mosquitoes	131	13
blister beetles	15	20
fish	59	27
amphibians	37	51
reptiles	139	50
birds (residents)	237	8
mammals	86	14

Source: *Natural Resources of Sri Lanka*, Natural Resources, Energy & Science Authority of Sri Lanka, 1991, p.218.

Table 4.6: Ranking of Ecosystems by biological diversity

1	moist evergreen lowland forests	high diversity
2	moist semi-evergreen forest	
3	lower montane forest	
4	upper montane forest	
5	riverine forests	
6	villus	
7	dry mixed evergreen forests	
8	thorn forests	
9	grasslands	low diversity
coastal systems		
1	coral reefs	high diversity
2	seagrass beds	
3	mangroves	
4	salt marshes	
5	sand dunes	low diversity
cultivated systems		
1	house gardens	low diversity
2	rubber lands	
3	tea plantations	
4	rice paddies	minimal diversity

Lanka has the highest levels of biological diversity. Indeed, the NSF Committee on Research Priorities in Tropical Biology identifies Sri Lanka as demanding special attention. Biological diversity is under threat in Sri Lanka primarily from the progressive reduction in its natural forests and other ecosystems and the selective exploitation of species (particularly for timber).

In light of the importance of the biodiversity issue in Sri Lanka, power sector projects will likely come under intense scrutiny from this perspective. On Table 4.6 we rank the major ecosystem categories according to estimated levels of biodiversity: although this ranking refers to plant diversity, in general high levels of plant diversity are accompanied by high levels of faunal diversity -- although the information on the Sri Lankan fauna, particularly invertebrates, is still poor. Nevertheless, it is clear from this overall ranking that the main issue for the power sector is the degree to which hydro projects and transmission line corridors impact forest lands of high biological diversity, and to which thermal generation projects on the coast impact the high diversity coastal systems (particularly coral reefs and seagrass beds).

It is not merely the loss of acreage that is of potential concern. Since most ecosystems require minimum contiguous areas for stable existence, fragmentation of habitats will be of significance for long term survival. Many of the high biodiversity wet zone forests are already highly fragmented-- for example in the Matara district, the 160km^2 of remaining wet zone forest is fragmented into 30 patches, the largest of which is no more than 1,000 hectares.

Clearly, detailed site specific studies need to be conducted at the project level EIS stage to examine whether or not a proposed project will in fact impact an endemic species. At the planning stage, however, information at this level of detail is not likely to be available. The best that can reasonably be done, therefore, is to develop a quantitative index that predicts the probability that a particular project, or combination of projects in a sectoral development plan, will impact endemic species or destroy habitats of high biodiversity. Such an approach is developed in Chapter 8.

Coastal Zone Issues

As the generation mix shifts from one that is predominantly hydro, to one in which large baseload fossil fueled plants play an increasing role, it is inevitable that sites will need to be found on the coast to accommodate such thermal plants. As argued in Chapter 3, imported coal is the most likely fuel for such plants, which implies that any inland location would incur substantial additional transportation cost penalties.

The economic importance of preventing environmental degradation in the coastal zone is well established.[14] Foreign tourism, an important source of foreign exchange, is largely focussed on its sandy beaches and coastal estuaries and lagoons, with over 80% of hotel rooms located on the coast.[15] The marine fishery industry provides employment to some 100,000 persons, and is the largest source of animal protein for the island.

The main environmental issue concerns the discharge of heated effluents into waters of the coastal zone. This zone may include one or more of the following communities or ecosystems:

- Coral reefs, sea grass beds, benthic communities, mangrove stands, rocky and other shores;
- Zooplankton and phytoplankton communities which are free floating;
- Nursery grounds for fish and prawns.

The occurrence of bottom living communities is likely to be highest in shallow bays. Their extent, diversity, and human use is also likely to be highest in such areas.

Coral reefs are very valuable systems, but coral organisms are highly sensitive to changes in environmental conditions, including temperature. Sea grass beds are also important areas for nursery grounds and high species diversity. Both coral reefs and sea grass beds experience damage at 2-3°C above ambient, with corals losing their symbiotic algae, and sea grass beds showing blade damage.

Another effect of temperature increase is the change in community structure, with heat tolerant species replacing heat sensitive species. The range of impacts will depend on whether there is a thermocline and the depth of the well-mixed layer. Two surveys by the Norwegian oceanographic survey vessel Nansen give a broad idea of the temperature structure of shelf in Sri Lanka. The thermocline lies at depths of 50 meters, differing slightly on the West coast with season, and showing greater variation on the East Coast. The well mixed layer extends down to circa 50 meters. Approaching the shore, therefore, coastal waters will be well mixed.

In Trincomalee Harbor, where depths well in excess of 50 meters exist within the harbor area, a thermal discharge into the surface water will not reach the bottom, and major hypolimnetic communities will remain unaffected. However, in shallower coastal waters, because the well mixed layer reaches the bottom (as is the case at the discharge point proposed for Trincomalee by BVI), impacts of the thermal effluent on benthic communities could be quite drastic.[16]

In general, neither phytoplankton nor zooplankton are thought to show drastic effects. Their distribution is wide, and loss of species is highly unlikely. Also, even in the natural environment their distribution is patchy and highly variable in time and space.

Where it is possible to release the thermal effluent into the surface layers of a stratified body of water, the impact on the biota would be minimal, as benthic communities would not be affected, and damage to plankton is minimal.

However, when the receiving water body is shallow, and usually well-mixed, ecological damages are probable. In addition to scouring action in the vicinity of the outflow, thermal effect will have all sorts of impacts on the benthic communities referred to earlier. Nevertheless, the evaluation of the impacts of thermal effluents is quite site specific, and needs to consider:

- The quantity of heat discharged, and the depths and circulation patterns of the receiving water body.
- The types of ecosystems in the area potentially impacted by the thermal plume;
- The extent of each such system, and area of potential damage or loss;
- The level of biodiversity in each system, and whether loss or change is acceptable;
- Indirect effects of ecosystem damage and change
- Whether heated water will lie astride important migration routes (e.g. prawns)

Certainly if there are important coral reefs in the vicinity, such systems would be considered inviolable. Important sea grass beds would also have very high values placed on them. In other cases, site specific information relating to the items listed above would be needed in order to make assessments. In most cases information on the overall composition of the community may be sufficient. On a site specific basis, values may be assigned to ecosystems, biodiversity, and the extent of areas affected.

With respect to the possible impact on local fisheries, fishing grounds for prawns often lie near coasts (as in Negombo, Chilaw) and there is migration between grounds and adjacent lagoons of juveniles and adults. Important effects can result from thermal effluents in the vicinity, especially in shallower waters.

Finfish grounds generally lie far away from the coast. There may be some impacts on fish eggs and larvae, especially of screen impingement at the cooling water intake, and of cooling system entrainment. There may also be direct effects of temperature increase. In most cases, these effects are not likely to be of a scale large enough to make a noticeable impact on the fishery. The loss of fish eggs and larvae due to natural causes is so large that the effects of thermal effluents are unlikely to be significant.

Notes

[1] Significant contributions to this Chapter were made by several consultants, notably Mr. P. Illangovan, presently National Programme Coordinator of the Metropolitan Environmental Improvement Program (MEIP), in the area of Air Quality; Professor K. D. Arudpragasam, former Chairman of the Central Environment Authority, in the area of aquatic ecology and biodiversity issues; Dr. L. R. Sally, head of the Environment Division of NBRO, in the area of water quality; and Mr. J. Kotalawala, formerly of the Mahaweli Development Ministry, in the area of land use impacts.

[2] However, during times of drought (as most recently in April 1992), these thermal units may run 24 hours a day, with the remaining limited hydro resources used for peaking purposes.

[3] For a review of the history of the Samanalawewa project, see e.g. L. De Silva, *Economic development projects: An analysis of legal processes and institutional responses*, Report to the Natural Resources and Environmental Policy Project, Colombo, Sri Lanka, 1993.

[4] Again, however, it is useful make a comparison to the scale of projects elsewhere where the resettlement impacts have become matters of major national (and international) debate. The two Narmada projects in India (Sardar Sarovar and Narmada Sagar), for example, would require resettlement of 170,000 people, but provide over two million ha of irrigated land (see e.g. J. Dixon, L. Talbot and G. Le Moigne, *Dams and the environment: considerations in World Bank projects*, World Bank Technical Paper 10, Washington, DC, 1989).

[5] Fortunately, schistosomiasis or bilharziasis, a disease often associated with impoundments in other tropical countries, is not found in Sri Lanka.

[6] For this reason, the proposed Upper Kotmale project would tap only two thirds of the Devon Oya in order to allow for sufficient flow to preserve the nearby Devon Falls that would otherwise also be eliminated by the project.

[7] A scientific study of water quality problems in the Kotmale reservoir is to be conducted by the Institute for Fundamental Studies.

[8] D. Johansson, *The Kotmale environment: A Study of the environmental impact of the Kotmale hydropower project in Sri Lanka*, Swedish International Development Authority Evaluation Report, Stockholm, 1989.

[9] This is a relatively high fraction for SO_2, but simply reflects the very low present use of fueloil for power generation and industry, and the relatively high use of auto-diesel which has a sulfur content of about 0.5% by weight.

[10] For an analysis of the air quality problems of the Colombo metropolitan area, see e.g. Metropolitan Environmental Improvement Programme, *Clean Air 2000, An Action Plan for Colombo*, 1992. The energy and greenhouse gas emission reduction implications of the measures proposed in this plan -- such as a vehicle inspection and maintenance program for diesel buses and trucks -- are examined further in P. Meier, M. Munasinghe and T. Siyambalapitiya, *Energy sector policy and the environment: A case study of Sri Lanka*, Environment Department, World Bank, Washington, DC, 1994.

[11] The issues underlying these assumptions are explored elsewhere, e.g. in M. Munasinghe, *Energy-environmental issues and policy options for developing Countries*, Proceedings, International Conference on Energy and Environment, Bellagio, Italy, Nov. 1990, Published by the Tata Energy Research Institute, Delhi, India.

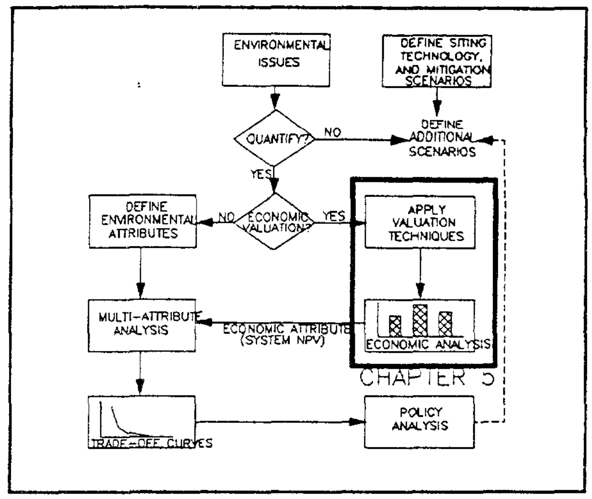
[12] An earthquake on the east coast of Luzon in July 1990, for example, caused a 2.5 meter fall in large areas of the coast, requiring large scale evacuation of coastal villages.

[13] The classic example is Shanghai, which subsided some 2.5 meters between 1920 and 1965. An artificial recharge program was, however, successful in arresting further subsidence. Parts of Bangkok are now subsiding several centimeters per year, and many other coastal cities in Southeast Asia face potentially serious subsidence problems.

[14] For a detailed review of Sri Lanka's coastal resources, see e.g., *Natural Resources of Sri Lanka*, Natural Resources, Energy & Science Authority of Sri Lanka, 1991, p. 218.

[15] Because of civil disturbances, foreign exchange earnings from tourism declined in the late 1980s; by 1990 tourist earnings had begun to recover somewhat, and amounted to SDR102million (compared to merchandise exports of SDR1,456million). During more normal times in the past, however, tourism was much more important; in 1982, earnings from tourism amounted to SDR133million, compared to merchandise exports of SDR919million in the same year.

[16] At the Turkey Point plant in Florida, where water temperatures are comparable to those in Sri Lanka, thermal discharges killed or damaged benthic organisms in over 100ha in the first two years of operation.



5. ECONOMIC VALUATION OF ENVIRONMENTAL IMPACTS

We now turn to economic valuation techniques and their application to power sector issues in Sri Lanka. The fundamental difficulty is that while a general framework for the valuation of environmental externalities and their incorporation into conventional benefit-cost analysis is well understood, the practical difficulties often preclude application to real situations.

We start the Chapter with a review of the general framework, and then give a brief summary of valuation techniques. After a discussion of the role of the discount rate and the treatment of risk and uncertainty, we review prior attempts at quantification of environmental externalities in Sri Lanka. We then examine some of the methods used to get around the difficulties of valuation, and attempt a preliminary analysis for Sri Lanka. The objective here is to examine the question of how the least cost expansion of electricity supply would be affected by given valuations for important externalities.

Basic issues in valuation

An established framework exists for including the costs of environmental damages into

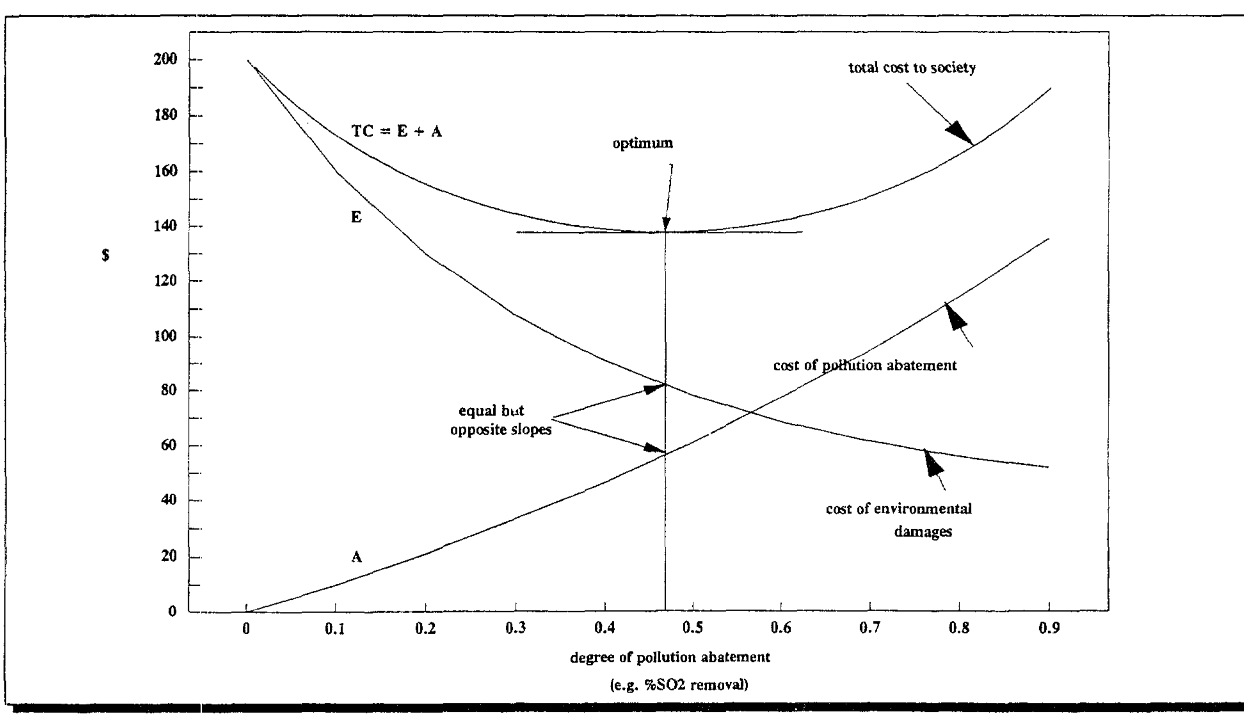


Figure 5.1: Optimum level of pollution abatement

conventional benefit/cost analysis, illustrated on Figure 5.1.[1] Curve A represents the cost of pollution abatement or environmental damage prevention: it is convex to reflect the increasing technological difficulties (and hence increasing marginal costs) of higher pollutant removal efficiencies.[2] Curve E depicts the costs of environmental damages inflicted by the facility in question: here the shape of the curve is more speculative, and may or may not take the form shown. Non-linearities in the dose-response function, threshold effects, and so on may make the actual shape of this curve quite complex. The total cost to society is the sum of these curves TC = E + A; generally the TC curve would exhibit a minimum somewhere within the range of technologically feasible pollution abatement options. At this minimum, the slopes of the E and A curves would be equal in magnitude but with opposite signs; in economic terms, at this point the incremental cost of abatement is exactly equal to the incremental benefit of avoided environmental damages.

Translating the theoretical framework into operational procedures for decision-making has proven difficult. Estimating the cost of pollution control is relatively easy, although removing the very last fraction of a pollutant from an emission stream may be subject to arguments about technical feasibility and therefore subject to considerable uncertainty about true costs. But estimating the cost of environmental damage associated with specific pollutants is generally much more difficult, for the following reasons:

1. Environmental impacts are highly site-specific. Unlike investment costs, which for any particular technology may typically vary from site to site or region to region by at most a factor of two, the environmental impacts of a particular technology may vary by orders of magnitude according to where the facility is located. For example, as noted above, in the case of Sri Lanka there are many hydro sites where no population resettlement may be required at all, whereas at others thousands of people may need to be relocated. Use of some "average" value would be entirely misleading in such cases.
2. Scientific uncertainty: our understanding of the cause-and-effect relationships is still very imperfect. Not only is it difficult to link ambient concentrations of harmful pollutants to specific sources of specific pollutants, estimating dose-response relationships requires detailed epidemiological studies that are very difficult to conduct in such a way that the results are reliable.
3. The absence of markets for environmental services: which means that prices, normally the best indicator of society's willingness to pay, are unavailable. As a result, indirect methods have to be used to value environmental services, the validity of which may be questioned.

The difficulties of economic valuation of environmental impacts are nowhere better illustrated than over the question of the health costs of air pollution, and the related questions of the valuation of human life.[3] What is established beyond much scientific doubt is that exposure of humans to pollutants emitted by fossil-fueled power plants -- particularly fine particulates and sulfates -- contributes to chronic diseases which result in higher death rates (mortality) and non-fatal sickness (morbidity).[4] But to quantify the relationship is extremely difficult.

Three steps are required. The first is to predict ambient concentrations of the pollutant involved. This is perhaps the easiest step, but even this may require meteorological information to drive air quality models that may simply not be available in developing countries.[5]

The second step is to quantify the dose-response function, which may require relatively sophisticated epidemiological evidence. Several issues arise in such a quantification -- such as the existence of any threshold effects (concentrations below which there is zero impact), the functional form of the relationship, and whether or not impacts are cumulative. Again, the validity of extrapolating dose-response functions that may be available from the industrialized countries to developing countries is entirely untested. Given the substantially different health histories of typical inhabitants, how valid would be a dose-response function developed for American cities to Colombo? Absent actual epidemiological studies in Sri Lanka, that is a question essentially impossible to answer.

The third step is most difficult of all, namely how to assign an economic value to a premature death.[6] A variety of methods have been suggested for this purpose, ranging from estimates of the discounted value of lost earnings[7] to surveys of the amounts in jury awards in damage suits involving death or disabling injuries. None of the available methods seem to offer very much practical value for application to developing countries: so much controversy would likely be engendered by the use of specific values that any benefits to internalizing such costs into the standard framework would be lost.

To be sure, not all impacts, or benefits, are subject to the same problems of measurement and valuation. Over the past decade a variety of techniques have been developed to value such costs and benefits, as we shall discuss below. However if one reviews the procedures adopted to date for practical application in regulatory proceedings of the developed countries, the difficulties of rigorous economic quantification become very evident. Indeed, the procedures adopted by many state regulatory commissions in the United States for actual decision-making purposes are quite crude, as reviewed below.

Valuation techniques

Conceptually, the total economic value (*TEV*) of a resource consists of its use value (*UV*) and non-use value (*NUV*). Use values may be broken down further into the direct use value (*DUV*), the indirect use value (*IUV*) and the option value (*OV*) (potential use value). One needs to be careful not to double-count both the value of indirect supporting functions and the value of the resulting direct use. One major category of non-use value is existence value (*EV*). We may write:

$$TEV = UV + NUV$$

or

$$TEV = [DUV + IUV + OV] + [NUV]$$

Figure 5.2 shows this disaggregation of *TEV* in schematic form. Below, for each valuation concept, we provide a short description of its meaning and a few typical examples of the

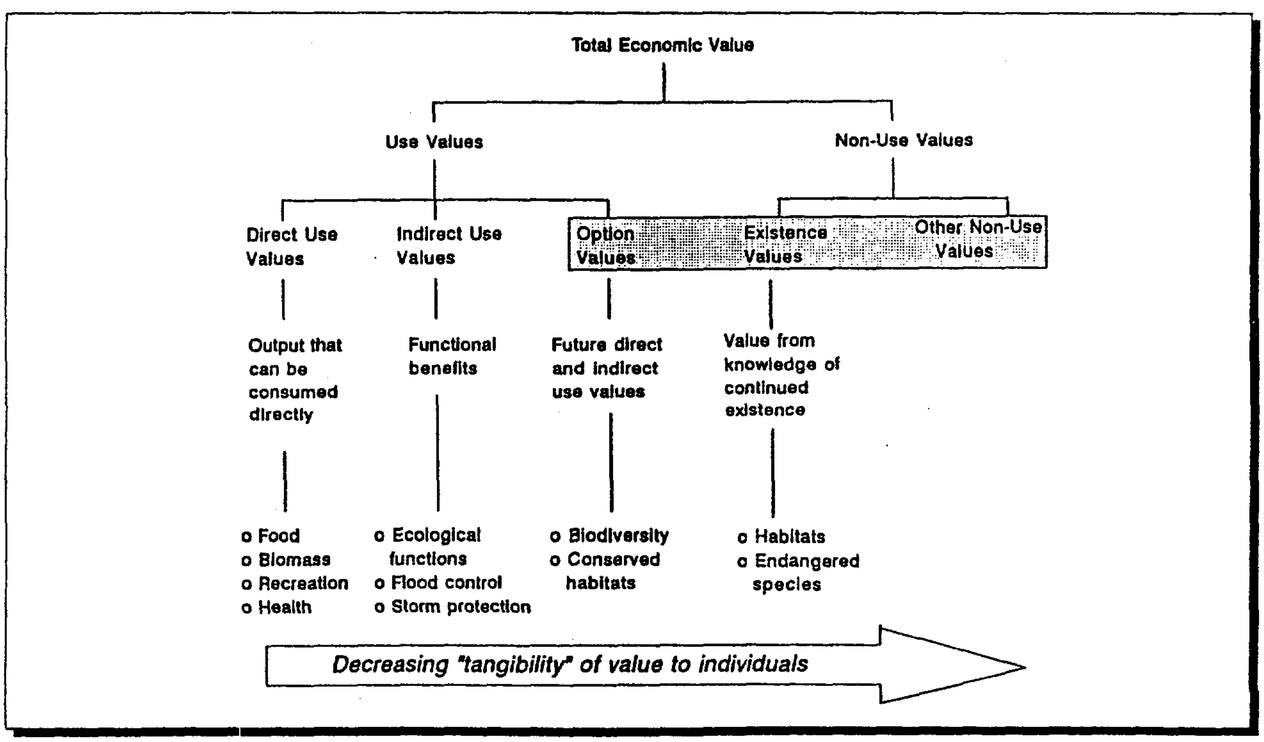


Figure 5.2: Categories of economic values attributed to environmental assets
(with examples from tropical forest, adapted from Pearce,1992)

Table 5.1: Taxonomy of relevant valuation techniques

	conventional market	implicit market	constructed market
based on actual behavior	change of productivity	travel cost	artificial market
	loss of earnings	wage differences	
	defensive or preventative cost	property values	
		proxy marketed goods	
based on potential behavior	replacement cost		contingent valuation
	shadow project		

environmental resources underlying the perceived value. Option values, bequest values and existence values are shaded, to caution the analyst concerning some of the ambiguities associated with defining these concepts -- as shown in the example, they can spring from similar or identical resources, while their estimation could be interlinked also. However, these concepts of value are generally quite distinct. Option value is based on how much individuals are willing to pay today for the option of preserving the asset for future (personal) direct and indirect use.[8] Bequest value, while excluding individuals' own use values, is the value that people derive from knowing that others (perhaps their own offspring), will be able to benefit from the resource in the future. Finally, existence value is the perceived value of the environmental asset unrelated either to current or optional use, i.e., simply because it exists.

A variety of valuation techniques may be used to quantify the above concepts of value. The basic concept of economic valuation underlying all these techniques is the willingness to pay (WTP) of individuals for an environmental service or resource, i.e., the area under the compensated or Hicksian demand curve. As shown in Table 5.1, valuation methods can be categorized, on the one hand, according to which type of market they rely on, and on the other hand, by considering how they make use of actual or potential behavior.

Actual behavior in conventional markets

The techniques summarized below rely mainly on directly observable actions or effects valued at market prices.

Change-in-productivity An investment decision often has environmental impacts, which in turn affect the quantity, quality or production costs of a range of outputs that may be valued readily in economic terms. The incremental output can be valued by using standard economic prices. This is the approach followed, for example, in the GTZ Masterplan to estimate the benefits of reservoir fisheries (see below).

For the approach to be successful for power sector applications, the most important requirement is the ability to establish a quantitative link between some particular aspect of project and the affected activity. For example, it is well established that the discharge of heated cooling water into bays or shallow ocean waters is likely to have a deleterious impact on some marine species.[9] But what one really needs here is the ability to predict, say, that a one degree temperature rise will cause an x percent reduction in fish catch, a two degree rise a y percent reduction, and so on.[10]

In Sri Lanka, however, since there are no existing once-through cooled plants that could serve as a baseline for "before" and "after" measurements, quantitative prediction of the impact at future plants is extremely difficult. In the case of Trincomalee, for example, all kinds of dire predictions were made as to the likely impacts of thermal discharges into Trincomalee Bay, assertions essentially impossible either to justify, or to refute except on grounds of general principle.[11]

Loss-of-earnings This approach is based on effects on health caused by pollution and environmental degradation. One practical measure that is relevant is the value of human output lost due to ill health or premature death. The loss of potential net earnings (called the human capital technique) is one proxy for foregone output, to which the costs of health care or prevention may be added (as a form of replacement/preventive expenditure). The above measure assumes that earnings reflect the value of marginal product and that medical treatment costs are well defined. The method also encounters difficulties when the cause-effect link between environmental quality and ill-health is unclear, or the sickness is chronic (i.e., of long duration).

This technique seeks to avoid ethical controversies associated with valuing a single life, attempting instead to place a value on the statistical probability of ill-health or death (akin to the actuarial values used by life insurance companies). Moreover, governments and public health authorities routinely set priorities and allocate health expenditures which affect human well-being. This in turn provides a baseline for determining implicit values placed by society on various health risks.

For the technique to be useful, the following conditions need to be present:

1. The cause and effect need to be demonstrably linked. For example, stagnant water pools downstream of a dam are demonstrably linked to breeding grounds of disease carrying mosquitoes. As argued previously, in the case of air pollution it may be difficult to isolate sources, and/or the incremental contribution of a specific facility may be hard to calculate because of general scientific uncertainties.
2. The related illnesses should be of limited duration and have no long term effects, thereby avoiding the complications introduced by valuations of life itself. Malaria might conceivably fall into this category, given the availability of modern treatments.
3. The costs of health care are known, and the value of the lost productive time is calculable. In the case of malaria in Sri Lanka, the costs of malaria treatment, and well as prophylaxis, can readily be determined.

In the particular example used here that seems appropriate to application in Sri Lanka -- namely the effort to value the health costs of malaria caused by inadequate streamflows immediately downstream of dams -- the key problem is quantification of the number of additional cases actually caused by the stagnant pools. As noted in the previous chapter, while there is some anecdotal evidence that some cases have occurred as a consequence of this problem, assigning some particular number of cases to a particular dam would be quite speculative.

Defensive or preventive cost. Often, costs may have been voluntarily incurred by communities or individuals to mitigate or undo the damage caused by an adverse environmental impact. For example, if the drinking water is polluted, extra filtration and/or purifying chemicals may need to be used. Then, such additional defensive or preventive expenditures (ex-post) could be taken as a minimum estimate of the benefits of mitigation. The assumption is that the benefits of avoided environmental degradation at least exceed the costs of avoidance. The advantage of the technique is that defensive or preventive outlays (already made) are easier to determine than the value of the original environmental damage. One weakness is the defensive actions are sometimes decided upon quite arbitrarily with little reliance on market forces, so that the costs bear little relation to the potential environmental benefit.

Recently, Harrington *et al.* (1989) evaluated the economic damages of a waterborne disease outbreak, emphasizing that the valuation of averting behavior requires the establishment of a relationship between observable defensive expenditures, and non-observable willingness to pay.

Potential expenditure valued in conventional markets: replacement cost and shadow project.

If an environmental resource that has been impaired is likely to be replaced in the future by another asset that provides equivalent services, then the costs of replacement may be used as a proxy for the environmental damage. This is an *ex-ante* measure similar in spirit to the (*ex- post*) defensive costs approach. It may be argued that the benefits from the environmental resource should be at least as valuable as the replacement expenses. For example, if the original project was a dam that inundated some forest land, then the shadow project might involve the replanting of an equivalent area of forest, elsewhere. Often, the equivalency criterion is hard to satisfy exactly --in the above example, the two tracts of forest may have the same volume of biomass, but could differ widely in terms of biodiversity. The replacement cost approach has been applied to the protection of groundwater resources in the Philippines, by determining the cost of developing alternative water sources (Munasinghe 1992).

Valuation Using Implicit (or Surrogate) Markets

Often, relevant market data is not available in directly usable form, to value environmental resources. In many such cases, analysis of indirect market data (e.g., using statistical and econometric methods) permits the valuation to be carried out implicitly. A variety of such surrogate market-based methods -- including travel cost, the "hedonic" methods (property value and wage differential), and proxy goods -- as well as their applicability under different circumstances, are described below.

Travel Cost. This method seeks to determine the demand for a recreational site (e.g., number of visits per year to a park), as a function of variables like consumer income, price, and various socio-economic characteristics. The price is usually the sum of observed cost elements like (a) entry price to the site; (b) costs of travelling to the site; and (c) foregone earnings or opportunity cost of time spent. The consumer surplus associated with the demand curve provides an estimate of the value of the recreational site in question. More sophisticated versions include comparisons (using regression analysis) across sites, where environmental quality is also included as a variable that affects demand (for a detailed survey, see Mendelsohn 1987 and Bockstael *et al.* 1991). Until a few years ago, most applications of this technique were to be found in the market economies, but quite recently, several examples have emerged involving developing world applications (Munasinghe 1993).

Property Value. In areas where relatively competitive markets exist for land, it is possible to decompose real estate prices into components attributable to different characteristics like house and lot size, proximity to schools, shops and parks, etc. (Cropper and Oates 1992). To value an environmental variable like air or water quality, the method seeks to determine that component of the property value attributable to the relevant environmental variable. Thus, the marginal WTP for improved local environmental quality is reflected in the increased price of housing in cleaner neighborhoods. This method has limited applicability in developing countries, because it requires a well-functioning housing market, as well as sophisticated information and tools of statistical analysis. Jimenez (1983) used this technique to explain changes in housing prices in a Manila slum area, upgraded partly due to water and sanitation service improvements.

Wage Differences. As in the case of property values, the wage differential method attempts to relate changes in an economic price variable (i.e., the wage rate), to environmental conditions. The underlying assumption is that there is some component of the wage that is determined by the environmental pollution or hazard associated with the job or work site. The technique is relevant when competitive labor markets exist, where wages (that reflect the marginal product of labor) equilibrate the supply and demand for labor (see earlier discussion on shadow pricing). One concern is that the approach relies on private valuations of health risks, rather than social ones. In this context, the level of information on occupational hazards must be high, for private individuals to make meaningful tradeoffs between health-risk and remuneration. Finally, the effects of all factors other than environment (e.g., age, skill level, job responsibility, etc.) that might influence wages must be accounted for, to eliminate bias and isolate the impacts of environment.

With the exception of commercial tourism, in developing countries travel costs to recreational amenities are unlikely to be meaningful and significant. In Sri Lanka the method might conceivably be used to value recreation benefits associated with hydro projects insofar as these lie at some distance to the bulk of the tourist activities, and the travel cost might therefore be viewed as significant. However, even for foreign tourists in such places, the journey itself could be part of the pleasure, and therefore not a disutility. However for the moment in Sri Lanka, there is no organized recreational development of any of the major reservoirs, so surveys of such occasional visitors that do come across the reservoirs would be of limited usefulness.[12]

The application of these hedonic methods would be difficult in developing countries, because of the presence of large distortions in both labor and real estate markets, and the fact that the notion of a willingness to pay for general environmental improvement may be implausible in very poor communities (Munasinghe, 1993). In Sri Lanka one might conceivably use the property value approach to examine the effect of pollution -- or other perceived environmental disutilities -- at the existing thermal stations in the Colombo area. With respect to power sector work, however, the problem at Sapugaskanda is that the refinery is the predominant industrial facility in the area, and it would be very difficult to isolate the impacts of the diesel generating station (particularly in view of the only sporadic operation of the Sapugaskanda facility in normal hydro years). It seems doubtful that any such attempts would yield conclusions sufficiently plausible to extrapolate to the anticipated impacts at the coal burning power plants of the future.[13]

Proxy marketed goods: This method is useful when an environmental good or service has no readily determined market value, but a close substitute exists which does have a competitively determined price. In such a case, the market price of the substitute may be used as a proxy for the value of the environmental resource. Barbier *et al*, (1991) provide an example involving marketed and non-marketed fish substitutes.

Valuation using constructed markets

In cases where market information cannot be used directly or indirectly, market-like behavior needs to be deduced through construction or simulation. The methods summarized below depend on direct questions, surveys or marketing experiments.

Artificial Market. Such markets are constructed for experimental purposes, to determine consumer WTP for a good or service. For example, a home water purification kit might be marketed at various price levels, or access to a game reserve may be offered on the basis of different admission fees, thereby facilitating the respective estimation of values placed by individuals on water purity or on the use of a recreational facility.

Contingent Valuation. When relevant market behavior is not observable, the contingent valuation method (CVM) puts direct questions to individuals to determine how much they might be willing-to-pay (WTP) for an environmental resource, or how much compensation they would be willing-to-accept (WTA) if they were deprived of the same resource. The contingent valuation method is more effective when the respondents are familiar with the environmental good or service (e.g., water quality) and have adequate information on which to base their preferences. CVM is likely to be far less reliable when the object of the valuation exercise is a more abstract aspect like existence value.

Generally, declared WTA tends to be significantly greater than the corresponding WTP. This may be partly attributable to "strategic bias" where respondents feel they would be better off inflating the amounts they would receive rather than the sums to be paid out, if the hypothetical questions posed were somehow to become a reality in the future. In the case of poorer individuals, WTP may be limited by the ability-to-pay, whereas WTA is not. The questionnaires have to be carefully designed, implemented and interpreted to overcome the above mentioned difficulties, as well as other types of bias Munasinghe (1990b) provides several early examples of the application of CVM to value the quality of electricity services in developing countries.

A recent review by Pearce and Markandya (1989) compared valuation estimates obtained from market-based techniques and CVM, using results from seven studies carried out in industrial nations. They found that the corresponding estimates overlapped within an accuracy range of plus or minus 60 percent. The conclusion is that CVM, cautiously and rigorously applied, could provide rough estimates of value that would be helpful in economic decision-making, especially when other valuation methods were unavailable.

The application of such methods in Sri Lanka would need a great deal of validation, and again for the immediate future represents a topic for academic research rather than for operational use in planning. For power sector application it conceivably has some potential for assessing existence values of unspoiled coastal resources (of relevance to siting large coal fired plants in remote areas of the south or east), and for estimating the health costs of air pollution (by evaluating the willingness to pay to avoid illnesses associated with air pollutants, or to avoid contracting malaria).[14]

Artificial markets Such markets could be constructed for experimental purposes, to determine consumer willingness to pay for a good or service. For example, a home water purification kit might be marketed at various price levels, or access to a game reserve may be offered on the basis of different admission fees, thereby facilitating the estimation of values placed by individuals on water purity or on the use of a recreational facility, respectively.

The discount rate

Economists typically use a forward-looking approach in which past (or sunk) costs and benefits are ignored, while a discount rate is applied to future costs and benefits to yield their present values. Standard criteria for cost-benefit analysis (CBA), such as the net present value (NPV) and internal rate of return (IRR) are derived in this way. The issue of choosing an appropriate discount rate has been discussed in the context of general CBA for many years (Dasgupta *et al.* 1972, Harberger 1976, Little and Mirrlees 1974). The long term perspective required for sustainable development suggests that the discount rate might play a critical role in intertemporal decisions concerning the use of environmental resources (Lind and Arrow 1982).

Two concepts mainly help to shape the discount (or interest) rate in a market economy. First, there is the personal rate of time preference of individuals which determines how they compare present-day with future consumption. Second, there is the rate of return on (or opportunity cost of) capital, which determines how an investment (made by foregoing today's consumption) would yield a stream of future consumption (net of replacement). In an ideally functioning market, the interest rate which equilibrates savings and investment, also equals both the marginal rates of time preference and return on capital. In practice, government policy distortions and market failures lead to divergences between the rates of time preference and return on capital. Furthermore, the social rate of time preference may be less than the individual time preference rate, because long-lasting societies are likely to have a bigger stake in the more distant future than relatively short- lived individuals.

The rate of capital productivity is very high in many developing countries, because of capital scarcity, and the rate of time preference also is elevated because of the urgency of satisfying immediate food needs rather than ensuring long term food security (Pearce and Turner 1990).

Projects with social costs occurring in the long term and net social benefits occurring in the near term will be favored by higher discount rates. Conversely, projects with benefits accruing in the long run will be less likely to be undertaken under high discount rates. Thus, some environmentalists have argued that discount rates should be lowered to facilitate environmentally sound projects meeting the CBA criteria. However, this would lead to more investment projects of all types, thereby possibly threatening fragile environmental resource bases. Norgaard (1991) argues that lowering discount rates can in fact worsen environmental degradation -- by lowering the cost of capital and thereby lowering the cost of production, more is consumed in the near-term relative to the case where discount rates were higher. Further, using a very low discount rate to protect future generations is inequitable, since it would penalize the present generation and increase inequalities across time periods -- especially when the present contained widespread poverty (Pearce 1991).

In order to facilitate such intergenerational transfers, one option is to impose a sustainability constraint, whereby current well-being is maximized without reducing the welfare of future generations below that of the current generation. In practice, this would entail monitoring and measurement of capital stocks (man-made, human and natural), and a broad investment policy which sought to ensure that compensating investments offset depreciation of existing assets (Pearce 1991). Theoretically, the aim would be to ensure that the overall stock of assets is preserved or enhanced for future generations, but practical application of this principle would be difficult.

In summary, the following conclusions may be reached, within the context of environmental cost-benefit analysis:

1. The standard opportunity cost of capital (e.g., 6-12 percent) may be used as the discount rate

2. Efforts should be made to ensure that compensating investments offset capital stock degradation arising from policy and project decisions;

3. In the case of projects leading to irreversible damage, CBA should be adapted to the extent possible, to include the foregone benefits of preservation in the computation of costs.

In this case study, therefore, in the absence of a compelling reason to employ different discount rates, we use a single discount rate for all present value calculations, namely 10%, which is used by the CEB for its system planning studies.[15]

Risk and Uncertainty

Risk and uncertainty are an inherent part of economic decisions, but the two concepts, though often mentioned in the same phrase, are operationally if not conceptually quite distinct. One talks of risk in situations where the probability distribution of the event can readily be established. The temporal distribution of rainfall and runoff, for example, or the risk of fire and accident, can readily be quantified as probability distributions.

Uncertainty, on the other hand, refers to events for which probability distributions cannot be established, either because the events are not replicable (because they have never occurred in the past, and there is thus no data upon which to base hypotheses), or because they are so complex that we cannot yet sort out cause and effect.

Risk probability and severity of damage could be used to determine an expected value of potential costs, which would be used in the CBA. However, the use of a single number (or expected value of risk) does not indicate the degree of variability or the range of probability values that might be expected. Additionally, it does not allow for individual perceptions of risk. The risk probability may be used to devise an insurance scheme to protect against the risk.

However, in the case of uncertainty, it is not possible to estimate the expected value of costs or insure against an unknown eventuality. The increasing scale of human activity, the complexity of environmental and ecological systems, and the lack of knowledge of how these systems might be affected, all emphasize the need to deal with uncertainty more explicitly. A cautious approach is the key to dealing with uncertainty. Global warming is an illustrative example. In the past, the greenhouse effect of CO_2 emissions was not known or recognized. At the present time, there is still considerable uncertainty about the future impacts of global warming, but given the large magnitude of potential consequences, caution is warranted.

The traditional and simple way of incorporating risk and uncertainty considerations in project level CBA has been through sensitivity analysis. Using optimistic and pessimistic values for different variables can indicate which variables will have the most pronounced effects on benefits and costs. We note that while sensitivity analysis need not reflect the probability of occurrence of the upper or lower values, it is useful for determining which variables are most important to the success or failure of a project. More sophisticated approaches to analyze risk and uncertainty are available (Braden and Kolstad 1991).

The issue of uncertainty plays an important role in environmental valuation and policy formulation. Option values and quasi-option values are based on the existence of uncertainty. Option value (OV) is essentially the "premium" that consumers are willing to pay to avoid the risk of not having something available in the future. The sign of option value depends upon the presence of supply and/or demand uncertainty, and on whether the consumer is risk averse or risk loving.

Quasi-option value (QOV) is the value of preserving options for future use in the expectation that knowledge will grow over time. If a development takes place that causes irreversible environmental damage, the opportunity to expand knowledge through scientific study of flora and fauna is lost. Uncertainty about the benefits of preservation to be derived through future knowledge expansion (which is independent of development) leads to a positive QOV. This suggests that the development should be postponed until increased knowledge facilitates a more informed decision. If information growth is contingent upon the development taking place, which is unlikely in an environmental context, then QOV is positive when the uncertainty regards the benefits of preservation, and negative when the uncertainty is about the benefits of the development.

Environmental policy formulation is complicated by the presence of numerous forms of uncertainty. As an illustration, Bromley (1989) identified six different aspects of uncertainty in the matter of air pollution resulting from acid deposition:

1. The identification of the sources of particular pollutants.
2. The ultimate destination of particular emissions.
3. The actual physical impacts at the point of destination.
4. Human valuation of the realized impacts at the point of destination of the emissions.
5. The extent to which a particular policy response will have an impact on the above mentioned factors.
6. The actual cost level and the incidence of those costs that are the result of policy choice.

Bromley suggests that the way in which policy-makers address these uncertainties depends on their perception of the existing entitlement structure. The interests of the future are only protected by an entitlement structure that imposes a duty on current generations to consider the rights of future generations (or, as he terms them, "missing markets" because "future generations are unable to enter bids to protect their interests"). In the absence of such a structure, decisionmakers may tend to follow a policy that ignores costs to future generations, and minimizes costs to current generations at the expense of the future. If the entitlement structure is adjusted, the policymaker can then examine three policy instruments to ensure that future generations are not made worse off:

1. Mandated pollution abatement;
2. Full compensation for future damages (e.g., by taxation);

3. An annuity that will compensate the future for costs imposed in the present. In the face of uncertainty, the first option would appear to be the most efficient.

Other important sources of uncertainty linked with environmental issues include uncertainty over land tenure (which leads to deforestation and unsustainable agricultural practices), and uncertainty of resource rights (which can accelerate the rate of depletion of a nonrenewable resource). Policymakers can address these issues by instituting land reforms, and by designing appropriate taxation policies that return economic rents to public sources rather than to private agents.

Prior efforts to value power sector externalities in Sri Lanka

The current state of the art for quantifying environmental factors in the power sector is well illustrated by the various Black and Veatch studies conducted in Sri Lanka in the 1980s for thermal options, and by the GTZ sponsored Electricity Masterplan conducted by a team led by Lahmeyer International.

The extent to which impacts were quantified for hydro plants is summarized on Table 5.2. Notice the distinction made between quantification of physical impacts, and economic valuation of those impacts. The judgements as to significance in the Sri Lankan context are elaborated in the discussion below.

Resettlement costs

The GTZ masterplan study contains a detailed analysis of the likely resettlement costs associated with all of the hydro projects examined. In the absence of detailed surveys of every site, the procedure was based upon the derivation of a generic resettlement project to derive a representative per household figure equivalent to about $7,250 per household. This was then applied to the estimated number of households to be resettled at each site.

Expressed as a fraction of the total capital cost, one observes very large differences across projects, as illustrated on Figure 5.3. Most importantly, there exist a substantial number of larger schemes that would displace zero population, with zero resettlement costs.

Table 5.2: Impacts of Hydro-electric projects

	impacts quantified?	impacts valued?
Costs		
lost production	yes	yes
health*	yes	partial
water quality	no	no
resettlement	yes	yes
Benefits		
flood control/ flow regulation	no	no
irrigation	yes	yes
fisheries*	yes	yes
recreation benefits*	no	no

* impacts not viewed as significant in Sri Lanka.

How do the aggregate estimates used by the GTZ Masterplan compare with more detailed, site specific studies conducted at the feasibility plan stage? The pre-feasibility study of the Upper Kotmale hydro project[16] estimated total relocation costs at Rs460million for 1900 households, equivalent to $6,500 per household, slightly lower than the GTZ Masterplan figure of $7,250/household. In general, we believe the GTZ estimate to be sufficiently reliable to be used as a basis for estimating relocation costs in system planning studies.

However, for reasons that are unclear, CEB uses only the direct project cost in its WASP system planning studies, and does not include estimated resettlement costs in the hydro project capital cost. While in most cases the numbers involved are quite small, in one or two cases (such as some of the Kukule project variants) resettlement costs account for almost 20% of the direct capital costs, which may certainly have some significant impact on generation cost comparisons across alternatives.

Opportunity costs of inundation

In addition to the cost of compensation to land owners, the GTZ Masterplan makes estimates of the opportunity costs of lost production as a result of inundation. The production losses

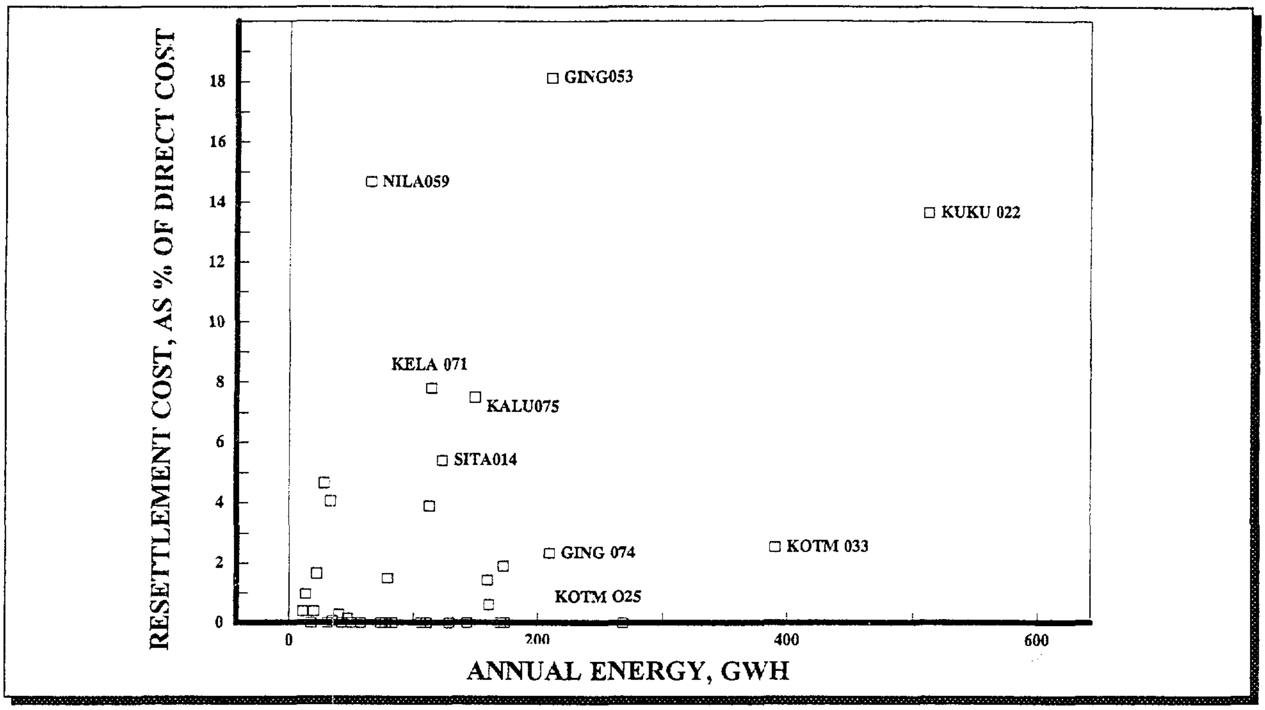


Figure 5.3: Resettlement cost penalties, as % of direct project capital cost

associated with each land use category are shown on Table 5.3: the overall opportunity cost then follows as the present value

$$\sum_{i}^{N} \frac{\sum_{j}^{M} A_j V_j}{1 + r^i}$$

where r is the discount rate (assumed at 12%), N is the planning horizon (assumed to be equal to the life of the plant, fifty years), V_j is the value per ha/year (from Table 5.3), and A_j is the area inundated of the j-th land use.

Table 5.3: Opportunity costs of inundation

land-use	$/ha/year
tea	528
coconut	764
paddy	379
rubber	175
agr. homesteads	100
sparse croplands	26
other crops	86
dense forest	228
forest plantations	890
forest scrub	10

Fisheries

The GTZ Masterplan attempted an explicit valuation of the potential value of fishery potential in hydro reservoirs.[17] The overall conclusion is that the likely monetary benefits are quite small (see Table 5.4). In view of the present Government policy of not promoting inland fisheries,[18] even the values assumed in the GTZ study are unlikely to materialize.[19]

The other related benefit usually associated with reservoirs in the developed countries are for recreational development -- water sports, boating, swimming, and so on. Given the absence of bilharzia and dangerous water snakes, the potential for such development in Sri Lanka is perhaps better than in many other tropical countries. However, the interest in these activities among the local population is very slight, and even boat trips in the large reservoirs have not been organized to date.[20] In any event, widespread access to the reservoirs has been limited for security considerations.[21]

Table 5.4: GTZ Estimates of fishery benefits

	fish yield (ton/yr)	fingerlings (1000/yr)	benefit ($US/year)
KEL A071	29	230	15,800
UMA 0042	5	39	2,750
KAL U075	44	355	23,800
GIN G052	76	610	41,200
DIY A008	8	68	4,250

Source: GTZ Masterplan, Volume S-5, Socio economic and environmental impact, p.18-20

Conclusions

In the case of hydro plants, most of the important environmental impacts were both quantified and valued as part of the GTZ Masterplan study. The valuation of resettlement and lost production costs, and fisheries and irrigation benefits, can be regarded as sufficiently reliable to be used in system planning studies of the type undertaken in this study. Flood control, health and water quality impacts were not quantified, but are also not likely to be significant in Sri Lanka (although in other countries these may in fact be significant).

Indeed, we recommend that at a minimum, the CEB begin adding the costs of resettlement to the capital cost of hydro plants in its planning studies. For a number of potential projects, these account for as much as an additional 5 to 20% of the direct capital cost. Since the resettlement costs do in fact represent real financial (and economic) costs to CEB, there is no reason to exclude them.

In the case of thermal plants, even the physical quantification of impacts has heretofore been very limited. The only aspect that has been rigorously treated to date at the system planning level is the calculation of SO_2, NO_x and ash emissions (in the GTZ masterplan). No efforts have been made to date to quantify the actual impacts associated with incremental air pollution from power plants. Such efforts, as we shall see in the next section, are however fraught with a number of conceptual and practical difficulties.

An illustrative computation: the health impacts of air pollution

To illustrate the difficulties of explicit valuation of impacts associated with human health, consider the incremental health impacts of a coal-fired plant in the Trincomalee, using the example of the impact of particulate pollution on health care costs associated with increased incidence of bronchitis. Respiratory diseases are a significant health issue in Sri Lanka, since they account for some 8% of hospital deaths, and 9% of all hospitalization cases.[22]

Based on the modelling studies in the EIS, average annual particulate concentrations, say C, in the vicinity of the plant are estimated to be in the range of 0.05 to 0.6 ug/m^3 (see Figure 5.4), averaging about 0.1ug/m^3.

Assume for the moment that dose-response functions estimated in the United States can be applied: for this purpose we use the compilations indicated on Table 5.5. Bronchitis is seen to be the most important morbidity affect associated with particulates -- although perhaps the principal conclusion of the data shown is that high degree of uncertainty associated with these estimates (as indicated by very high standard errors). These dose-response functions can be interpreted as the probability, say α, that an individual will contract bronchitis in any one year if exposed to 1 ug/m^3 of particulates for the entire year.

To calculate the cost of hospitalization care, we divide the total expenditure by the Ministry of Health (Rs 2.746billion in 1988) by the number of hospital admittances (1.2million in 1988) for a unit admittance cost, *U*, of Rs2,288 (or about 57$ per case). Unfortunately we are not aware of any estimates of the cost of hospital care for specific respiratory diseases, nor were we able to find any data on the length of the average hospital stay for respiratory illness admissions, much less on the fraction of all bronchitis cases that resulted in a hospital admission.

Table 5.5: Dose-response functions

victims	Sulfur Dioxide	Sulfate	Nitrogen Dioxide	Oxidants	Nitrate	Particulates
Mortality						
Males 18-44	0.5 (1)	20 (20)	3 (1)	0	-20 (20)	1.5 (10)
45-64	20 (15)	500 (100)	-30 (20)	0	-150(200)	-1 (100)
Females 18-44	1 (0.6)	11 (3)	0 (0.5)	0	5 (7)	0.3 (0.6)
45-64	20 (12)	320 (40)	-25 (10)	0	170 (200)	1 (10)
Morbidity						
Bronchitis	-9 (60)	4470(2500)	0	0	0	360 (350)
Lower Respira.	75 (100)	792 (600)	0	0	0	0
Croup	750 (100)	792 (600)	0	0	0	0
Pneumonia	13 (50)	500 (1000)	0	0	0	0
Acute	4 (8)	45 (100)	0	600	0	7 (2)
Vegetation	2.1 (4.3)	21 (30)		17 (18)		0.1 (2)
Materials		193 (200)		175 (200)		19 (51)

Numbers in parentheses are standard errors of the coefficients. Mortality responses are in 10^{-6} deaths per ug/m^3 person-year. Morbidity is measured in 10^{-6} sickness cases per ug/m^3 person-year. Vegetation losses are in dollars per ton of emission. Material losses are in mills per ug/m^3 per person.

Source: R. Mendelsohn, An Economic Analysis of Air Pollution from Coal-fired Plants, Journal of Environmental Economics and Management, 7, 30-43, 1981.

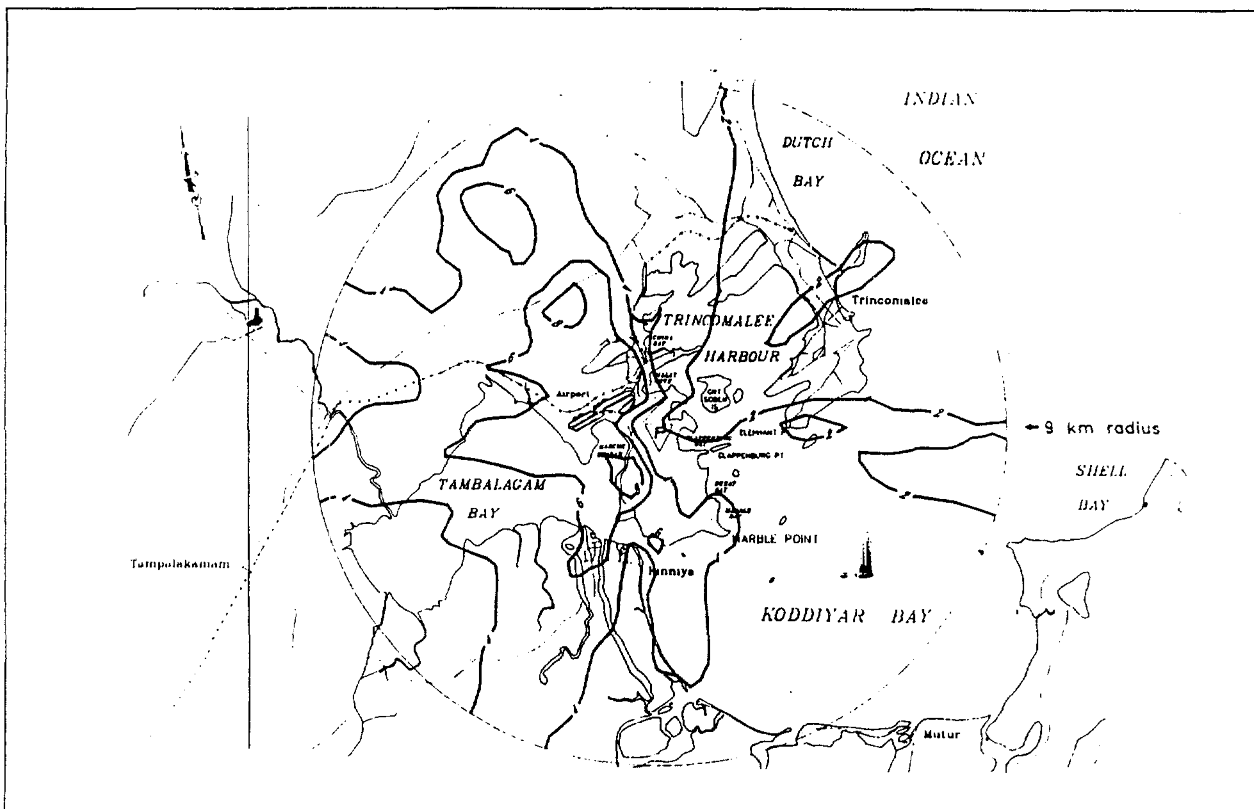


Figure 5.4: Average annual concentrations of particulates, 900Mw plant

With all these assumptions at hand, the total health care costs for bronchitis, H_b, calculate to

$$H_b = \alpha P\ C\ U$$

which, for an affected population of P = 100,000 evaluates to

$$H_b = (360 \times 10^{-6})\ (100{,}000)\ (0.1)\ (57) = \$205 \text{ per year.}$$

It is useful to recapitulate explicitly all of the assumptions made in this analysis, stated here in the form of questions:

1. *Can dose-response functions developed in the United States be applied to Sri Lanka?* The most important issue here is the general health profile, particularly of the older population; given the substantial differences in age distribution, at the very minimum one needs to correct for age differences. If one uses total population as a basis, the likely direction of error is to overestimate the impact (since the proportion of the population in the group most at risk, namely those over 45, will be smaller in Sri Lanka than in the U.S.).

2. *Is the dose-response function linear?* That is, does a doubling of the concentration of particulates imply twice the risk? There is a great deal of evidence to suggest that the dose response function for respiratory diseases is non-linear, the greatest danger lying in even very short periods of exposure to high concentrations -- which is the reason for the use of maximum 3 and 24-hour health based standards. The likely direction of error here is to underestimate the impact.

3. *Are the costs of hospital treatment the best (or even a reasonable) measure of the health impact.* A better measure may be the willingness to pay to avoid the illness in the first place, which one would expect at a very minimum include some relationship to lost earnings during hospitalization. We know of no such study for Sri Lanka.

Approaches to dealing with valuation difficulties

Even in the United States, there remains a wide gulf between practical application of valuation techniques in decision-making, and what is theoretically possible. The practical application of valuation techniques is perhaps most advanced in the Pacific northwest, where the Bonneville Power Administration now makes routine use of valuation techniques for natural resources that may be affected by hydro developments.[23] But this is still the exception rather than the rule: in most states, where public utility commissions regulate investor-owned utilities, the approaches adopted to force utilities to consider environmental externalities are still quite simplistic.[24] This is in large part a consequence of the much greater difficulties associated with valuing externalities associated with thermal generation, which represents the main generation resource in most of the United States.[25]

Quantitative consideration

The first approach, which is by far the most common, goes in the literature under the name "quantitative consideration". Its basic postulate it that although the ability to quantify, much less value, actual environmental damages from residual pollutant emissions is still far too difficult to be attempted, certain technologies are judged to have a much lesser impact on the environment than others. Therefore, the results of conventional benefit cost analysis that is used by utilities as an investment criterion need to be adjusted to reflect this judgement. Many State regulatory commissions in the United States have therefore introduced rules to make such adjustments in favor of demand-side management options and renewable generation technologies seen as environmentally beneficial.

One variant of this approach calls for direct adjustment of levelized per kwh cost that is the typical yardstick of comparison of supply and demand side resources. For example, the Northwest Power Planning Council and the Vermont Public Service Board reduce the cost of demand side options by 10% in their least cost planning process. In addition, Vermont also increases the cost of supply-side resources by 5%. The State of Wisconsin uses a 15% "non-combustion adder".

Another approach is to make an adjustment in the allowable rate of return. Washington and Montana, for example, have introduced statutory provisions for an additional 2% rate-of-return on energy conservation investments, while Connecticut provides for an additional 5%.[26]

For a variety of reasons such approaches do not appear applicable in developing countries. The most important is not that they appear arbitrary, but that in the United States there exists a process by which such rules are arbitrated and subject to public debate among the affected parties such that there is a reasonable presumption that the rules adopted do reflect the appropriate balance between economic and environmental objectives as perceived by the ratepayers and environmental advocates within the States concerned. The established procedures for regulatory Commission hearings, intervention by affected parties, the procedures for appointment and/or election of Commissioners who make the final decisions, and recourse to the court system all ensure that the final result does reflect the societal consensus on how the objective should be weighted. Indeed, it has been argued that "determining how much more to pay for clean power is a political judgement, not merely a technical determination" (Weil,1991).

In developing countries such institutions are patently absent. Clearly it would be inappropriate for system planners, or those in the International Financial Institutions who evaluate the adequacy of least-cost planning procedures, to select such values according to their own judgement. Whether or not it is possible to do better, and to provide at least an explicit basis for quantifying the environmental costs is of course the subject of this case study.

Using control costs as a proxy

A second approach to avoiding the difficulties of explicit valuation of power sector externalities is to use control costs as a proxy for environmental damages. This is an approach that has come into increasing favor with regulatory commissions in the United States.[27] The basic assumption has been stated as follows: since legislators and regulators have rationally weighed the social costs of pollution control when enacting standards, it follows that the marginal benefit of reducing pollution equals the marginal cost that industry now bears. Therefore, according to this rationale, marginal pollution control costs would be a reasonable estimate of the social costs of the residual emissions (i.e. emissions released beyond levels mandated by applicable standards).

This seems like an extremely poor argument, for it is quite obvious that most standards have been adopted without knowledge of the true damage costs. Moreover, even the advocates of the use of control costs seem to have limited confidence in their calculations, and resort to arbitrary adjustments of their own. Thus, for example, in New York, the proxy for environmental damage of residual air emissions is based on weighted averages of advanced and low cost control technologies: the CO_2 value is taken as 20% of the low cost technology, the SO_2 value is taken as 80% of the advanced technology plus 20% of the low cost technology; and NO_x as 20% of the advanced and 80% of the low cost technology. The adjustment for CO_2, for example, is justified on grounds of the " .. controversy that surrounds the relationship between greenhouse gas emissions and global warming". However, making arbitrary adjustments seems a poor approach to dealing with the uncertainties involved.

The location dependence of impacts are widely ignored. For example, NO_x emissions in the costing system of New York are penalized at 5.5 cents/kwh, independent of location. Why NOx emissions from a peaking unit located near an urban load center (especially in a non-attainment area) should be penalized at the same rate as those in remote areas is not obvious if the intent is to capture the impacts of externalities.

In some cases the use of preventative expenditures as a measure of environmental damage may be perfectly plausible: for example, disruptions to the groundwater table during penstock tunneling at hydro projects (of the type encountered at the Samanalawewa) may reasonably be valued at the cost of supplying water to affected users by bowsers. However, for this assumption to be true, one needs to be sure that there are no irreversible impacts (such as any extensive root damage to trees).

In other cases, the approach can only provide a lower bound to the actual value. For example, the cost of a forest plantation to offset inundated land at a reservoir does replace lost timber by sequestering an equivalent amount of CO_2, and provides offsetting benefits to watershed management, but would not compensate for the cost of reduced biodiversity.

However, one of the main pitfalls in use of these methods is the temptation to confuse costs and benefits. For example, in an ADB study of environmental considerations in energy planning, it is asserted that:

> "The costs of controlling or reducing SO_2 emissions are used here to provide a value for the environmental damage caused by these emissions. . . . For example, if there is a general target to achieve 40% reduction of SO_2 from power generation, then the costs of meeting that target could be calculated by multiplying 40% of SO_2 emissions from power generation by the cost of FGD. *The resultant value would represent an economic valuation of the environmental benefits to be gained by meeting that target, or the damages caused by failing to do so* [our emphasis]"[28]

Yet reference to Figure 5.1 should suffice to point out that this assertion is incorrect: such an estimate in fact says absolutely nothing about benefits at all. One can simply hope that indeed the costs of the impacts are in fact less than the costs of avoidance: but if at all possible one ought to estimate the damage function itself.

Environmental Costing: a preliminary analysis for Sri Lanka

Suppose for the moment that appropriate damage cost estimates were available for Sri Lanka. Would the least cost generation mix change if these damage costs were included in the analysis? Even if we recognize that American damage cost estimates were not appropriate, could one make estimates of how large such costs would have to be in order for them to make a difference to the expansion plan?

Definition of environmental costs

A first problem concerns the definition of "environmental costs", since there have been all kinds of wild claims in the literature as to the proportion of capital and operating costs of power plants are attributable to environmental regulations.[29] One in fact needs to make a clear distinction between what constitutes normal engineering practice, and what constitutes the incremental costs of environmental protection measures. For example, it is quite routine to include the costs of resettlement at hydro-electric plants into project capital costs (even though, as noted, in the past the Ceylon Electricity Board has not done so as part of its system expansion planning studies), and many aspects of pollution control have become routine components of good engineering design. Thus ash disposal ponds at coal fired power plants should be regarded as part of normal engineering practice, and no one would today consider sluicing ash directly into a receiving water. Table 5.6 illustrates the definitions that are used in this report.

Emission coefficients

There are several problems in attempting to define appropriate emission coefficients for application to Sri Lanka. Mindless application of coefficients drawn from the literature is particularly problematic, because so many of these coefficients are presented without any specification of the precise assumptions used: one suspects that this is at least in part a consequence of the fact that so many of these presentations are themselves reviews of other work.[30]

A second problem is the proliferation of units one encounters in the literature, including gm/GJ, lbs/Kwh, lbs/Mwh, gms/Kwh, kg/million Kcal, and lbs/million Btu, among others. Clearly there is a need to chose some

Table 5.6: Definition of environmental costs

	normal engineering practice	additional environmental control costs
ash disposal	disposal ponds	incremental costs of leachate control, impervious liners, etc.
air emission control	ESP to 99.5% removal	FGD, NOx controls, sludge disposal associated with FGD.
thermal discharges	once-through cooling for steam cycle, mechanical draft towers for diesels	cooling towers, long ocean outfalls and diffusion systems for once-through cooling, cooling ponds
stack design	stack height as defined by EPA as "good engineering practice"	tall stacks for long-range dispersion

consistent specification. Expressing emission coefficients in terms of weight units per kwh is the worst option, because it is absolutely essential that the assumptions concerning heat content of the fuel, and the heat rate of the plant, are made explicit. This is because as one examines various pollution control options, the technical performance of the plant itself varies: FGD systems will degrade net plant heat rates, which in turn has an impact on the level of CO_2 emissions.[31] In this Chapter, therefore, all emission coefficients are expressed as Kg/million Kcal of energy input.

Table 5.7 summarizes our review of emission coefficients found in the literature, all brought to the same set of units. The data are organized for the major technology groups (conventional coal without FGD, clean coal, etc), and both reported units and our conversion to Kg/10^6KCal are shown. Coefficients are given for NO_x, particulates and CO_2. However, SO_2 emissions are generally calculable directly from sulfur contents of the fuel involved.

The conventional economic analysis

On Table 5.8 we show a conventional cost analysis of the main generation alternatives considered in the 1991 CEB generation expansion planning studies; all of the critical assumptions, including capital costs, interest during construction (IDC), discount rate (10%), O&M costs, fuel costs, heat rates etc. are as per this study. In addition to the various thermal options, we have also included here two hydro projects: Broadlands, which is an element of the current least cost plan, and Kukule, which is not. Figure 5.5 summarizes the results, using year 2000 fuel costs.

The results of the least cost plan can be predicted from this analysis: the coal plants without FGD systems are cheaper than diesels, whether or not the diesels are fitted with catalytic NO_x control systems. In the case of the Trincomalee unit, even with an FGD system costs are some 10% lower than for diesels. One might therefore expect that the least cost plant brings in coal units as soon as they are permitted (in the 1991 study it is assumed that the earliest a coal plant might be introduced is 1999, and indeed the first 150Mw unit enters the least cost plan in that year). Combined cycle units are seen to be more expensive than diesel, and do not therefore enter any of the least cost plans.

For peaking and intermediate loads, Broadlands has a substantially lower cost than combustion turbines, while Kukule has a higher cost. Again, it is predictable that Broadlands would enter the least cost plan, while Kukule does not. However, as noted in the 1991 generation study, there are indications that the Broadlands project may have substantially higher construction costs than what was indicated by the 1986 feasibility study, which need to be confirmed before proceeding with the project.

Damage Estimates

As noted, there are no Sri Lankan studies of damage costs related to the pollutants associated with the power sector; the lack of

Table 5.7: Emission coefficients

				------as reported		------	assumed	--converted to Kg/10.6Kcal--		
	source		units	NOx	part.	CO2	[btu/kwh]	NOx	part.	CO2
		conventional coal, no FGD								
1	MassPUC	"high sulfur"	[lbs/mwh]	5.86	0.029	2118	9000	1.173	0.006	424
2	ADB-low	?	[gm/kwh]	3	1	900	10185	1.169	0.390	351
3	ADB-high	?	[gm/kwh]	6	5	1000	10185	2.338	1.948	390
4	cc	average	[lb/10..6Btu	0.607	0.15	209		1.094	0.270	377
5	USDoE	1.2%S,uncontrolled	[lb/kwh]	0.0094	0.0094	1.96	9400	1.802	1.802	376
6	ITB	ombilin						1.094	0.064	349
7	ITB	buk.a						1.094	0.071	406
8	ITB	buk.a						1.094	0.060	381
9	ITB	buk.a						1.094	0.204	374
10	ITB	kali						1.094	0.153	380
11	ITB	kali						1.094	0.246	382
		clean coal								
12	USDoE	coal steam+FGD/ESP	[lb/kwh]	0.0094	0.000752	1.96	9400	1.802	0.144	376
13	OECD	coal steam+FGD,Bagh	[g/GJ]	775	13			3.245	0.054	
14	Pace	AFBC	[lb/10..6Btu	0.3	0.01	209		0.540	0.018	377
15	USDoE	AFBC	[lb/kwh]	0.00376	0.000282	1.96	9400	0.721	0.054	376
16	PLC	AFBC	[lb/kwh]	0.003	0.0015	2.09	10000	0.540	0.270	377
17	Pace	IGCC	[lb/10..6Btu	0.06	0.01	209		0.108	0.018	377
18	USDoE	IGCC	[lb/kwh]	0.000451	0.000090	1.88	9010	0.090	0.018	376
19	PLC	IGCC	[lb/kwh]	0.0006	0.0015	2.09	10000	0.108	0.270	377
20	OECD	coal,PFBC,Baghouse	[g/GJ]	215	13			0.900	0.054	
		oil								
21	ADB-low	oil,steam	[gm/kwh]	1.5	0.2	720	10185	0.584	0.078	281
22	ADB-high	oil,steam	[gm/kwh]	3.8	2	800	10185	1.481	0.779	312
23	Pace	oil,steam,2.2%Sresid	[lb/10..6Btu	0.357	0.174	169		0.643	0.313	304
24	Pace	oil,steam,0.5%Sresid	[lb/10..6Btu	0.357	0.055	169		0.643	0.099	304
25	Pace	CT,1%S distillate	[lb/10..6Btu	0.498	0.036	161		0.897	0.065	290
26	GTZ	gasoil CC	[gm/kwh]	1.447	0.0201	631	8124	0.707	0.010	308
		diesel								
27	GTZ	diesel	[g/GJ]	750	10			3.141	0.042	300
28	BVI	diesel+NOxcontrol/cata	[g/GJ]	75	10			0.314	0.042	300
		gas								
29	Pace	Gas,steam	[lb/10..6Btu	0.428	0.003	110		0.771	0.005	198
30	Pace	Gas CC	[lb/10..6Btu	0.42	0.003	110		0.757	0.005	198
31	ADB-low	Gas CC	[gm/Kwh]	1.4	very low	390	6824	0.814		227
32	ADB-high	Gas CC	[gm/Kwh]	1.8	very low	410	7582	0.942		215
33	GTZ	Gas CC	[gm/Kwh]	0.9928	0.0089	476	8124	0.485	0.004	233

(1) Massachussets Public Utilities Commission
(2) ADB, Environmental Considerations in Energy Planning
(3) OECD Emission Controls in Electricity generation and Industry, Paris 1988
(4) USDepartment of Energy

Table 5.8: Generation cost analysis

		diesel	diesel	mawella	mawella	trinco	trinco	gas	comb.	Broadlands	Kukule
			+NOx control		+FGD		+FGD	turbine	cycle		
fuel		3.5% S	3.5% S	coal	coal	coal	coal	diesel	diesel	hydro	hydro
unit installed capacity	[Mw]	20	20	150	150	300	300	22	68	40	144
base capital cost	[$/kw]	1045	1045	1511	1511	956	956	524	871	1477	1655
pollution control	[ ]		0.08		0.17		0.17				
overnight capital cost	[$/kw]	1045	1129	1511	1768	956	1119	524	871	1477	1655
construction time	[years]	3	3	6	6	6	6	2	2	4	6
interest during construction	[$/kw]	142	153	443	518	280	328	46	77	274	485
total capacity cost	[$/kw]	1187	1282	1954	2286	1236	1446	570	948	1751	2140
life	[years]	20	20	30	30	30	30	20	20	50	50
plant factor	[ ]	0.78	0.78	0.75	0.75	0.690	0.690	0.78	0.78	0.414	0.316
discount rate	0.1										
capital recovery factor	[ ]	0.1175	0.1175	0.1061	0.1061	0.1061	0.1061	0.1175	0.1175	0.1009	0.1009
annual capital cost	[$/yr]	139.42	150.57	207.27	242.50	131.14	153.43	66.96	111.30	176.57	215.85
annual O&M cost, fixed	[$/Kw/year]	13.032	13.032	5.436	6.636	5.436	6.636	3	8.316	1.872	1.872
varaible O&M cost	[$/kwh]	0.00325	0.00325		0.0035		0.0035	0.00439	0.00439		
fuel		fueloil,3.5%	fueloil,3.5%	coal,cifM	coal,cifM	coal,cifM	coal,cifM	diesel	diesel		
10..6KCal/unit		10000	10000	6660	6660	6660	6660	10000	10000		
sulfur content,by weight	[ ]	0.035	0.035	0.010	0.010	0.010	0.010	0.005	0.005		
uncontrolled emissions	[KgSO2/10.6K	6.993	6.993	3.000	3.000	3.000	3.000	0.999	0.999		
	[lb/10..6Btu]	3.52	3.52	1.51	1.51	1.51	1.51	0.50	0.50		
% sulfur removal	[ ]	0	0	0	0.8	0	0.8	0	0		
SO2 emissions	[kg/kwh]	0.0149	0.0149	0.0068	0.0014	0.0067	0.0014	0.0029	0.0018		
fuel case		2000	2000	2000	2000	2000	2000	2000	2000		
gross heatrate	[KCal/Kwh]	2134	2134	2269	2269	2232	2232	2908	1803		
	[Btu/kwh]	8468	8468	9004	9004	8857	8857	11540	7155		
efficiency	[ ]	0.40	0.40	0.38	0.38	0.39	0.39	0.30	0.48		
auxiliaries	[ ]										
FGD system	[ ]				0.05		0.05				
net heat rate	[KCal/Kwh]	2134	2134	2269	2382	2232	2344	2908	1803		
fuelcost	[$/10..6Kcal]	13.94	13.94	8.53	8.53	8.53	8.53	21.17	21.17		
capital cost	[mils/kwh]	20.4	22.1	31.5	36.9	21.7	25.4	9.8	16.3	48.7	78.1
fuel cost	[mils/kwh]	29.7	29.7	19.4	20.3	19.0	20.0	61.6	38.2	0.0	0.0
O&M cost	[mils/kwh]	5.2	5.2	0.8	4.5	0.9	4.6	4.8	5.6	0.5	0.7
total	[mils/kwh]	55.3	57.0	51.7	61.7	41.6	50.0	76.2	60.1	49.2	78.8

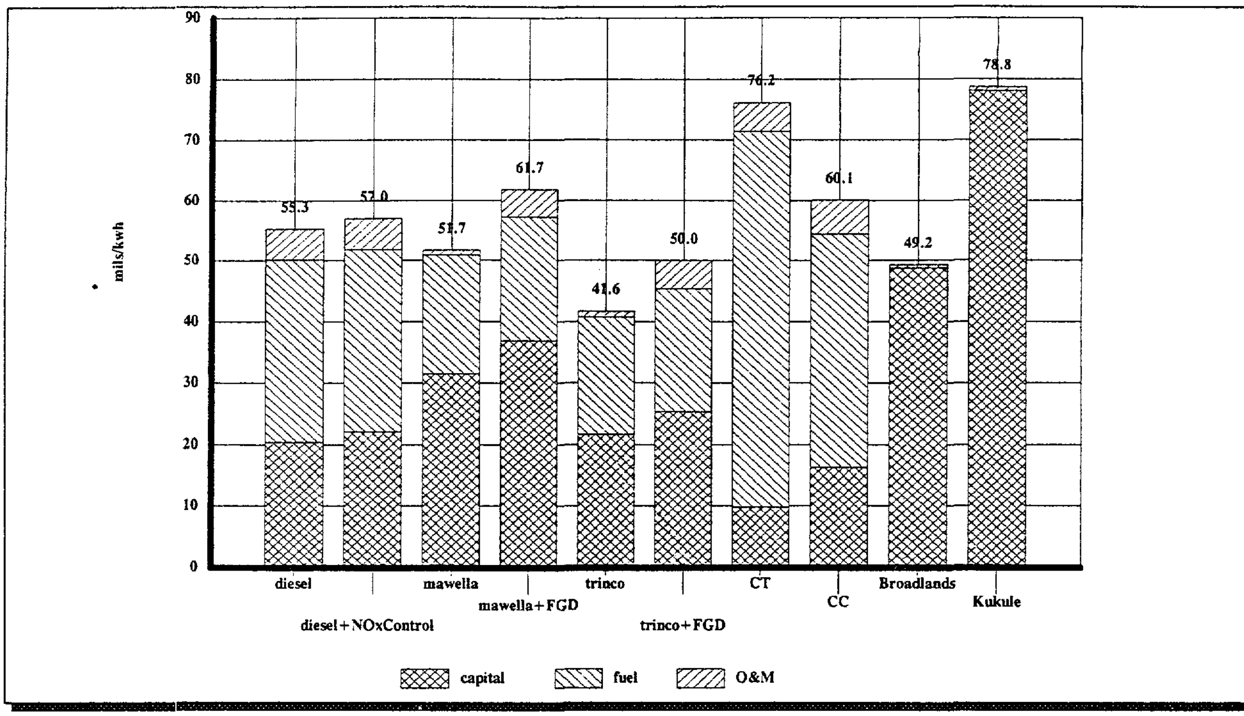


Figure 5.5: Generation cost analysis

epidemiological studies that might provide evidence of any relationship between air pollution and health effects is hardly surprising given the lack of data on ambient air quality. In any event there are so many more urgent public health problems that have merited the attention of researchers. Consequently one is dependent upon studies done elsewhere: the most appropriate (or certainly the least inappropriate) are the estimates used by the New York and the Massachusetts Public Utility Regulatory Commissions, and those derived by the Pace University study. Table 5.9 summarizes the estimates therein described for the principal pollutants associated with fossil fuel combustion. The regulatory commission estimates are based on control costs; the Pace estimates are based on an exhaustive review of damage cost estimates, largely from the United States.

A close inspection of the Pace damage cost estimates reveals that most of the total damage

Table 5.9: Damage estimates associated with fossil fuel emissions, in $/ton

	CO_2	partic.	SO_2	NO_x
Pace	15	2618	4466	1804
Massachusetts	22	360	1500	5000
New York	1.1	333	832	1832

Source: Pace University Center for Environmental Legal Studies, *Environmental Costs of Electricity*, Oceana Press, New York, 1990.

Table 5.10: Damage estimates by source (in UScents per lb)

	partic.	SO_2	NO_x
mortality	0.33	1.72	0.39
morbidity	0.03	0.05	0.29
materials		0.12	0.01
crop damage			0.01
visibility	0.83	0.14	0.17
total	1.19	2.03	0.82

Source: Pace University Center for Environmental Legal Studies, *Environmental Costs of Electricity*, Oceana Press, New York, 1990.

cost is attributable to mortality and morbidity effects, or, in the case of particulates, to the degradation of visibility (see Table 5.10). The health costs are based on a value of \$4,000,000 per death, and \$400,000 per non-fatal but disabling illness: estimates in the U.S. literature run as high as \$12,000,000 per death. It seems very unlikely that estimates based on jury damage awards or lost earnings in Sri Lanka would yield values as high as this. Similarly, it is very doubtful that visibility would be given as high a value by the average Sri Lankan as is the case in the U.S.

If these values are likely too high, how might they be adjusted?. One expedient might be to adjust them by the ratio of per capita GNP; in 1990 the Sri Lanka per capita GNP stood at \$418,[32] while the United States value is \$20,910. Using this ratio would provide a value per death of \$80,000 (or 3.2million Rupees). Some in the study team were of the view that figures as low as \$25,000 might be appropriate in light of road accident statistics. Others pointed to the lack of modern diagnostic equipment at Hospitals as a guide, noting the absence of CATSCAN equipment (costing about \$500,000) that would certainly, over the lifetime of its use, save at least 10 lives (from which one would infer from the unwillingness to pay a cost of \$50,000). In short it was difficult to find a consensus as to what would be an appropriate value; in the analysis that follows we therefore simply used 10% of the Pace estimates in an effort to be conservative.

The Pace estimate for carbon damage is based on the costs of reforestation to replace an equivalent quantity of carbon, rather than on any estimate of the actual damages likely to result from global warming. The value of 15 \$/ton CO_2, or 55 \$/ton of Carbon, is at the high end of the range of most of the values one encounters in the literature.[33] Estimates cited in an ICF/EPA report suggest a carbon sequestration cost of \$14-\$15, based on a sequestration rate of 1.81-2.26tons/acre/year;[34] the SERI estimate is \$5-16/ton Carbon per year. These are all for forestry programs in the United States. They are likely to be conservative in terms of application to Sri Lanka for two reasons; the cost of forestry programs is likely to be lower, and growth rates in tropical forests are arguably faster than in the temperate zones of the United States. Nevertheless, whatever the location of carbon fixing, a \$15/ton cost seems reasonable for use in this preliminary assessment.

Results

With these various assumptions now in place, we can now extend the original generation cost analysis to include the explicit valuation of environmental externalities. The Pace estimates of damages for fossil fuel emissions have been adjusted to reflect the lower values associated with human life (for which, as noted, we use a value of \$400,000).

In the case of the hydro projects we account for two types of externalities: the cost of resettlement and the opportunity costs of lost

Table 5.11: Greenhouse gas releases from the Kukule project

	tons C/ha	ha	1000 tons C	methane adjustment	net impact 1000tons CO_2
dense forest	250	500	125		458.3
scrub	50	200	1		3.7
tea	10	660	6.6		24.2
rubber	100	600	60		220.0
paddy		4960		U	U
mixed trees	80	1000	80		293.6
total		4960	272.6	U	999.6

Source: crop data from the GTZ Masterplan study. Carbon content of the standing biomass are study team estimates. U indicates that no estimate was attempted.

production. The impact of the Kukule project on CO_2 emissions is shown on Table 5.11. This is by far the largest project in the GTZ inventory of remaining hydro projects in terms of reservoir area, and hence in terms of potential impact on CO_2 stemming from the removal of vegetation.

It might be noted that since the high dam variant of the Kukule project would inundate some 2,000ha of paddy, one might also argue for a positive impact on greenhouse gas emissions attributable to the reduction in methane emissions. However, the loss of paddy at the Kukule project would likely be offset by increases in paddy at the locations to which resettled residents are moved: this same argument is much less likely to apply to other forms of vegetation lost at the project.[35] Moreover, the required calculations would be extremely sensitive to assumptions made about CO_2/CH_4 equivalency (which depend on time horizons used). In light of these uncertainties we elect simply to ignore the CH_4 impact, albeit recognizing that the offset could be significant.[36]

With these estimates in hand, we can now modify the calculations presented in Table 5.8, as indicated on Table 5.12. The upper portion of this table are the same as in Table 5.8, but we have added a number of rows at the bottom of the table to account for unit damage costs, emission factors, and the equivalent mils/kwh environmental damage cost. The results are summarized on Figure 5.6. The CO_2 externality cost indicated for Kukule (of 3.76mils/kwh) is based on the CO_2 figure derived on Table 5.13 (of about 1 million tons of CO_2), and using the appropriate capital recovery factor (10% discount rate over 50 years) for levelization purposes. The 8.98 mils/kwh shown for "other externalities" at Kukule are based on levelization of resettlement costs and the opportunity costs of lost production. The corresponding entires for Broadlands are zero, given the negligible reservoir area.

Thus, when externalities are taken into account, the following conclusions are evident:

1. Broadlands continues to be an attractive hydro project (albeit with the qualifications concerning capital costs noted above).
2. For baseload, combined cycle plants now appear more attractive than diesels, but still less attractive than the Trincomalee coal project.
3. The use of FGD systems at the coal plants does not seem warranted: the costs of FGD systems exceed the avoided damages.

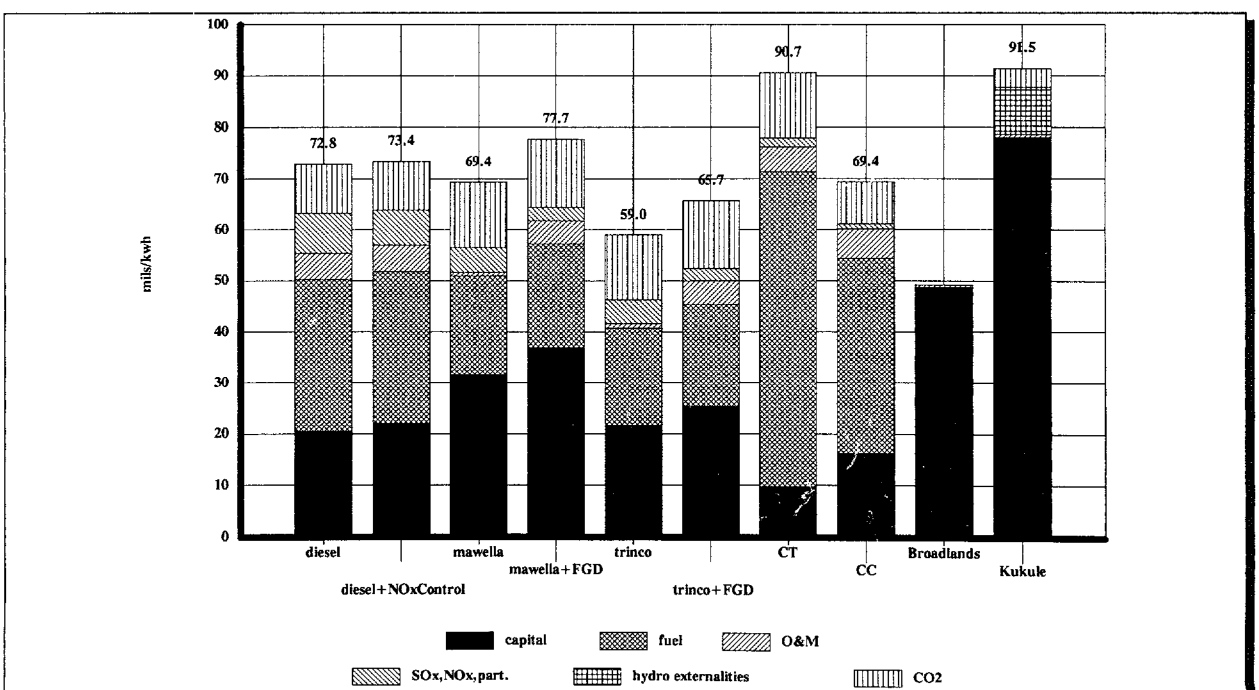


Figure 5.6: Generation cost comparisons including environmental externalities

Table 5.12: Generation cost analysis with externality values included

			diesel	diesel	mawella	mawella	trinco	trinco	gas	comb.	Broadlands	Kukule
				+NOx control		+FGD		+FGD	turbine	cycle		
fuel			3.5% S	3.5% S	coal	coal	coal	coal	diesel	diesel	hydro	hydro
unit installed capacity	[Mw]		20	20	150	150	300	300	22	68	40	144
base capital cost	[$/kw]		1045	1045	1511	1511	956	956	524	871	1477	1655
pollution control	[ ]			0.08		0.17		0.17				
overnight capital cost	[$/kw]		1045	1129	1511	1768	956	1119	524	871	1477	1655
construction time	[years]		3	3	6	6	6	6	2	2	4	6
interest during construction	[$/kw]		142	153	443	518	280	328	46	77	274	485
total capacity cost	[$/kw]		1187	1282	1954	2286	1236	1446	570	948	1751	2140
life	[years]		20	20	30	30	30	30	20	20	50	50
plant factor	[ ]		0.78	0.78	0.75	0.75	0.690	0.690	0.78	0.78	0.414	0.316
discount rate		0.1										
capital recovery factor	[ ]		0.1175	0.1175	0.1061	0.1061	0.1061	0.1061	0.1175	0.1175	0.1009	0.1009
annual capital cost	[$/yr]		139.42	150.57	207.27	242.50	131.14	153.43	66.96	111.30	176.57	215.85
annual O&M cost, fixed	[$/Kw/year]		13.032	13.032	5.436	6.636	5.436	6.636	3	8.316	1.872	1.872
varaible O&M cost	[$/kwh]		0.00325	0.00325		0.0035		0.0035	0.00439	0.00439		
fuel			fueloil,3.5%	fueloil,3.5%	coal,cifM	coal,cifM	coal,cifM	coal,cifM	diesel	diesel		
10..6KCal/unit			10000	10000	6660	6660	6660	6660	10000	10000		
sulfur content,by weight	[ ]		0.035	0.035	0.010	0.010	0.010	0.010	0.005	0.005		
uncontrolled emissions	[KgSO2/10..6K(		6.993	6.993	3.000	3.000	3.000	3.000	0.999	0.999		
	[lb/10..6Btu]		3.52	3.52	1.51	1.51	1.51	1.51	0.50	0.50		
% sulfur removal	[ ]		0	0	0	0.8	0	0.8	0	0		
SO2 emissions	[kg/kwh]		0.0149	0.0149	0.0068	0.0014	0.0067	0.0014	0.0029	0.0018		
fuel case			2000	2000	2000	2000	2000	2000	2000	2000		
gross heatrate	[KCal/Kwh]		2134	2134	2269	2269	2232	2232	2908	1803		
	[Btu/kwh]		8468	8468	9004	9004	8857	8857	11540	7155		
efficiency	[ ]		0.40	0.40	0.38	0.38	0.39	0.39	0.30	0.48		
auxiliaries	[ ]											
FGD system	[ ]					0.05		0.05				
net heat rate	[KCal/Kwh]		2134	2134	2269	2382	2232	2344	2908	1803		
fuelcost	[$/10..6Kcal]		13.94	13.94	8.53	8.53	8.53	8.53	21.17	21.17		
capital cost	[mils/kwh]		20.4	22.1	31.5	36.9	21.7	25.4	9.8	16.3	48.7	78.1
fuel cost	[mils/kwh]		29.7	29.7	19.4	20.3	19.0	20.0	61.6	38.2	0.0	0.0
O&M cost	[mils/kwh]		5.2	5.2	0.8	4.5	0.9	4.6	4.8	5.6	0.5	0.7
total	[mils/kwh]		55.3	57.0	51.7	61.7	41.6	50.0	76.2	60.1	49.2	78.8
externalities	[mils/kwh]		17.5	16.4	17.6	16.0	17.3	15.7	14.5	9.4	1.0	12.7
TOTAL COST, NO EXTERNALITIES	[mils/kwh]		55.3	57.0	51.7	61.7	41.6	50.0	76.2	60.1	49.2	78.8
TOTAL COST, WITH EXTERNALITIES	[mils/kwh]		72.8	73.4	69.4	77.7	59.0	65.7	90.7	69.4	50.2	91.5
damage costs												
SO2	[$/ton]		446.6	446.6	446.6	446.6	446.6	446.6	446.6	446.6	446.6	446.6
NOx	[$/ton]		180.4	180.4	180.4	180.4	180.4	180.4	180.4	180.4	180.4	180.4
particulates	[$/ton]		261.8	261.8	261.8	261.8	261.8	261.8	261.8	261.8	261.8	261.8
CO2	[$/ton]		15	15	15	15	15	15	15	15	15	15
emission factors	source>		27	28	5	5	5	5	25	26		
NOx	[Kg/10..6KCal]		3.141	0.314	1.802	1.802	1.802	1.802	0.897	0.707		
particulates	[Kg/10..6KCal]		0.042	0.042	1.802	1.802	1.802	1.802	0.065	0.010		
CO2	[Kg/10..6KCal]		300	300	376	376	376	376	290	308		
SO2	[mils/kwh]		6.66	6.66	3.04	0.64	2.99	0.63	1.30	0.80	0.00	0.00
NOx	[mils/kwh]		1.21	0.12	0.74	0.77	0.73	0.76	0.47	0.23	0.00	0.00
particulates	[mils/kwh]		0.02	0.02	1.07	1.12	1.05	1.11	0.05	0.00	0.00	0.00
CO2	[mils/kwh]		9.60	9.60	12.79	13.42	12.58	13.21	12.65	8.34		3.76
other externalities	[mils/kwh]											8.98
TOTAL DAMAGE COSTS	[mils/kwh]		17.50	16.41	17.63	15.96	17.35	15.70	14.47	9.37	1.00	12.74

However, the SO_2 damage costs do not include any acid rain impacts.

4. The dispatch order does not change when environmental externalities are taken into account. Hydro plants are still dispatched first, followed by coal plants, then diesels, and combustion turbines last. However, this conclusion is specific only to Sri Lanka, and environmental dispatch rules may well change the merit order in other systems.

Obviously, the third conclusion is largely a matter of how one values health damage costs. Another way of looking at the issue is to ask the question of what the health damage cost would need to be for FGD systems to be justified. On Figure 5.7 we plot the ratio of the total cost (i.e. including externality costs) of a coal plant at Trincomalee with an FGD system to a coal plant without an FGD system, as a function of the value placed on human life. FGD systems are obviously justified -- meaning that the total social costs are lower -- when this ratio is less than unity. The corresponding mortality valuation is about $1.6million. Therefore, if Sri Lankan decision makers value human life at more than $1.6million, then the additional cost of an FGD system is justified.[37]

These conclusions are subject to a number of other general qualifications. The most important is that we are here using generic values for damages, that are independent of location. That is, the critical assumption is that the population distribution around Trincomalee is the same as the average of the population distributions around the plants for which health damage estimates were made in the United States. Because this assumption is so critical, we need to make site specific calculations of population exposures, a task attempted in later Chapters of this report.

Implications for the case study

Whatever the theoretical potential for the use of valuation methods of the type examined in this Chapter, there are some formidable obstacles to their practical application in developing countries.

As a first general conclusion it is probably fair to assert that the more significant the externality from the perspective of its public perception, the more difficult it is to value (as exemplified by the ultimate impact of death). Moreover, those impacts that can be readily valued result in relatively small changes to the economic decision calculus.

This point is illustrated on Table 5.13, in which we examine the case of potential hydro sites in Sri Lanka. As part of the GTZ Electricity Masterplan, the value of lost production was estimated for all of the potential hydro sites examined: the values ranged from 10$/ha/year for scrub land to $530 for tea. When expressed as a fraction of the total project cost, the resultant estimates are very small indeed. Similar results are obtained for the costs of resettlement. Kukule is the only hydro project where such costs are seen to be significant, and likely to affect the overall economic feasibility of the project.[38]

Yet it is almost certain that such valuation methods do not in fact reflect the actual impacts of reservoirs, as perceived by those who are displaced. Except in the unlikely event of voluntary resettlement, it is hard to imagine that monetary compensation is sufficient to offset the loss of ancestral lands, the uprooting of established communities, and so on. Indeed, if monetary compensation to those displaced were sufficient, there would be no public opposition to the project from such affected individuals, a situation that is clearly not true. On the other hand, it is also quite well established that the most vocal opponents of reservoir projects -- in Sri Lanka as elsewhere in both the industrialized and developing countries -- are not necessarily those who are most seriously affected.

In short, whatever the theoretical promise of being able to internalize all of the significant externalities into a single benefit cost criterion, in practice there are well defined limits to what can be done. It is this limitation that points to the use of multi-attribute decision analysis methods. And it is to such methods that we turn in the next chapter.

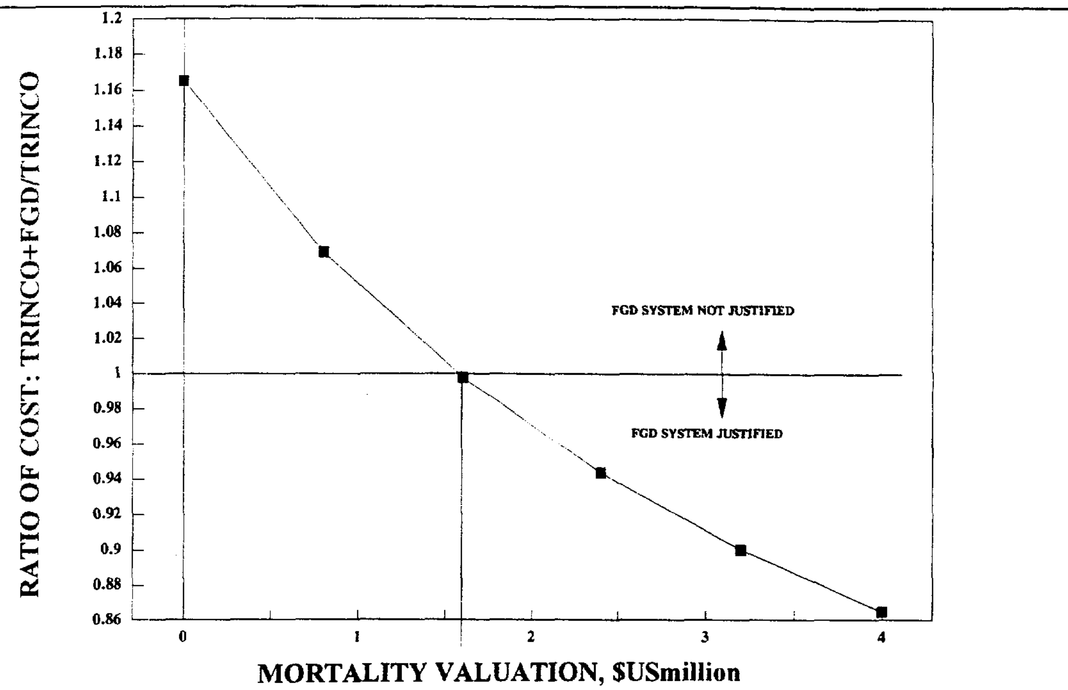


Figure 5.7: FGD systems and mortality valuation

Table 5.13: Value of inundated land at potential hydro sites

Site	generation cost, c/kwh[a]	value of land inundated as % [b]	resettlement cost, as %
Upper Kotmale	3.5	0.30	0.00
GING 074 (Ging Ganga)	4.3	1.02	3.90
Madula Oya	5.1	0.00	0.00
UMA 034 (Uma Oya)	5.4	0.11	0.00
KELA 085	5.6	0.00	0.00
MAHW 263 (Moragolla)	6.0	0.55	0.00
BELI 015	6.1	0.00	0.00
HASS 006	6.3	0.02	0.47
KOTM 033	7.3	0.53	1.23
Kukule (144Mw,High Dam)	7.5	7.28	5.48

Notes: [a] total capital and operating costs over a 50-year lifetime, using a 10% discount rate.
[b] present value of forest and agricultural land inundated, over 50year lifetime at 10%.
Source: GTZ, *Masterplan for the Electricity Supply of Sri Lanka*

Notes

[1] Several excellent discussions have appeared lately, e.g. P. Joskow, Weighing environmental externalities: Let's do it right!, Electricity Journal, May 1992, p.53-66; or, for a more exhaustive presentation, D. Dodds and J. Lessor, *Monetization and quantification of environmental impacts*, State of Washington Interagency Task Force on Environmental Costs, Washington State Energy Office, June 1992.

[2] The first 20% removal of a pollutant is less costly than the second 20%, and so on. Removal of the last 1-5% of a pollutant is often prohibitively expensive, even if technologically feasible.

[3] For a brief non-technical discussion of some of the problems involved see e.g. A. Kneese, *Measuring the Benefits of Clean Air and Water*, Resources for the Future, Washington D.C. 1984.

[4] It should be noted that SO_2 itself is not generally believed to be a major cause of air-pollution related health effects. Rather, very small particulates (those under 10 microns in diameter, known as PM10) appear to be the most immediate agent. However, SO_2 emissions react in the atmosphere to form sulfates, which *are* believed to be a significant fraction of the harmful PM10. For a discussion see e.g. J.Graham *et al.*, *Direct health effects of air pollutants associated with acidic precursor emissions*, United States Environmental Protection Agency, State of Science Report 22, Vol II, National Acidic Precipitation Assessment Program (NAPAP), Washington, DC., December 1989.

[5] The extrapolation of meteorological data from one location to another is likely to be very controversial: in the Trincomalee EIS, in the absence of local information, the consultants used data from Guam for the detailed air quality modelling. Whatever the scientific validity of such assumptions, such extrapolations are bound to become matters of public controversy.

[6] Nowhere have these issues been dealt with in greater depth than in connection with nuclear plants, upon which subject there now exists a truly vast literature. The United States Nuclear Regulatory Commission, for example, has grappled with the valuation problem for decades, and is currently engaged in a re-examination of the $1000 per person-rem of exposure it has used for the last 20 years as a basis for justifying safety improvements at nuclear power plants. The questions involved are exhaustively discussed in L.A. Nieves and J.J.Tawil *The Economic Costs of Radiation-Induced health Effects: Estimation and Simulation*, Report NUREG/CRRR-4811, U.S. Nuclear Regulatory Commission, Washington, DC. 1988.

[7] A variety of ethical objections arise here: a first implication is that the worth of the usually male head of household wage earner is higher than that of his unemployed spouse. Second, it implies that the worth of an American life may be worth several hundred times that of an individual in a developing country.

[8] For a discussion and example of this see B. Aylward and E. Barbier (1992).

[9] It is however true that in some cases, particularly where thermal discharges are into areas of relatively cold water, fishing may in fact improve in the vicinity of the plume. However, once the fish have become accustomed to the new temperature regimes, plant shut-downs (whether planned or unplanned) will cause sudden temperature changes and potentially massive fish-kills (The most celebrated example of which was the 1978 fish kill at the Oyster Bay nuclear plant in New Jersey).

[10] In a case study given in J. Dixon and M. Hufschmidt, *Economic valuation techniques for the environment: A case study workbook*, Johns Hopkins University Press, Baltimore, 1984, the estimation of losses of marine product resources caused by the development of Tokyo Bay rests upon observations of the fish catch in the Bay over time.

[11] For example "..a great deal of light tackle fishing is done within the Bay and just outside it and a thermal power plant will essentially reduce the marine fauna in the vicinity". The consultants response was "..the thermal plume may in fact improve fishing. In any case we see no basis on which to predict that it will reduce the fauna in the vicinity." Trincomalee EIS, Volume II, p.E-51.

[12] The first tourism development project at a major reservoir has recently been proposed at the Victoria dam. This involves a luxury hotel and condominium development, with several golf courses, and targeted largely at the Japanese market. Visitors would be brought in from the

Colombo airport by helicopter. However, because of concerns over the security of the dam, development of water-based recreation (water-skiing, boating) have been deferred to some future stage.

[13] One might of course make the attempt to estimate emissions at other types of industrial facility that are significant sources of air pollution as well -- such as cement plants. However, for the moment we conclude that such efforts are still very much at the stage of academic research, and cannot be recommended for practical work.

[14] One of the writers conducted a simple WTP experiment of this question among the participants in a recent training course on environmental impact assessment held in Kotmale, an area that has recently experienced an increase in malaria. The WTP to avoid malaria among those who had *never had Malaria* was almost *twice as high* as those who had had malaria. In fact, none of the participants below the median age of 37 had ever contracted Malaria, while 90% of the participants over the median age had experienced at least one case. These results illustrate some of the difficulties of properly controlling such surveys.

[15] In the sensitivity analyses presented in Chapter 9, the same rate is applied to both the system cost attribute as to environmental impacts.

[16] Japan International Cooperation Agency, *Feasibility Study on Upper Kotmale Hydroelectric Power Development Project*, August 1987.

[17] It should be noted that the GTZ Masterplan makes very careful distinction between primary and secondary costs (which it defines as including resettlement costs, and the opportunity costs of lost production from inundated lands), and properly uses the latter in its system planning studies.

[18] There does not appear to be any commercial fishery activity in the Kotmale, Victoria and Randenigala Reservoirs. GTZ reported that there were some 22 fishermen active in the Mousakelle reservoir, with an annual catch of about 22 tons/year.

[19] This policy appears to be based upon religious reasons. The potential for development of inland fisheries was already suggested in the various Mahaweli project studies, and the Inland Fisheries Department had begun stocking the renovated irrigation tanks in a number of areas. However, all these activities have now ceased. It does appear that there is some unauthorized fishing activity in some of the reservoirs; however, the Department of Wildlife has issued no permits.

[20] The only recreational opportunity that may have significant potential is sport fishing for foreign tourists: trout fishing in the up-country rivers and pools was very common during the colonial era.

[21] See note 12, *supra*.

[22] See Ministry of State for Health National Health Development Plan, 1990, Tables 1.5 and 1.6. According to Department of Census Statistics, some 8% of deaths recorded by the Vital Registrar are also attributable to respiratory diseases.

[23] For good examples of the use of the available techniques, including many of the methods discussed in this chapter, see e.g. Biosystems Analysis, Inc., *Methods for valuation of environmental costs and benefits of hydroelectric facilities: a case study of the Sultan River project*, Report to the Bonneville Power Administration, 1984; or P. Meyer *et al.*, *Calculation of environmental costs and benefits associated with hydropower development in the Pacific Northwest*, Bonneville Power Administration, Report DE-AC79-83BP11546, 1986.

[24] see e.g. Temple, Barker & Sloane, *Environmental externalities: An overview of theory and practice*, Report EPRI CU/EN-7297, Electric Power Research Institute, Palo Alto, CA, 1991.

[25] There are many critics of utility regulatory commissions entering into the arena of environmental valuation. One of the harshest is Ruff (1992), who concludes ".. thus, while utility regulators might try to second guess and improve upon the work of the environmental authorities, this is a short-run, second or third- best alternative to better environmental policies implemented by environmental authorities, and is not the long-term solution to anything". Joskow, *op.cit.* makes similarly strong arguments about the dangers involved.

[26] There is little discussion of the actual effects of such quantitative consideration measures upon decisions in the literature, perhaps because the procedures appear so far removed from rigorous cost/benefit analysis that nobody has bothered to examine them systematically.

[27] Perhaps the leading exponent of this approach is Massachusetts, which recently held hearings to re-examine the course set a few years ago that provided for valuation of environmental externalities based on control costs. The hearing, which generated thousands of pages of testimony, and was characterized by contentious and often conflicting testimony by experts, was typical of such proceedings: in the end, the Commission decided to retain its earlier approach, noting, *inter alia*, ".. the Department is reaffirming its strong commitment to the concept of considering environmental externalities in resource decision-making. At times, policy-makers have to accept a "second best" solution as a means of moving in a desired direction". See Commonwealth of Massachusetts, Department of Public Utilities, Docket 91-131, Nov. 10, 1992.

[28] Risk and Policy Analysts Limited, *Introduction to the spreadsheets for economic analysis*, Report to the Asian Development Bank, August 1991, p.5.

[29] What is and is not included in "environmental control costs" is a significant issue, because many of the figures cited in the literature are quite vague about definitions. For example, an OECD study (International Energy Agency, Emission Controls in Electricity Generation and Industry, Paris, 1988) quotes a German study that environmental controls represented a 47% increase in capital cost (SOx control 19%, NOx control 9%, particulate controls 6%, effluents 6% and noise, waste and other 7.5%). It also quotes EPRI as having estimated pollution control costs to amount to 40% of the capital cost, and 35% of operation costs. Clearly, without very precise definitions of exactly what is meant, for example, by "particulate controls", such estimates are not very useful.

[30] The coefficients suggested by ADB (Asian Development Bank, *Environmental Considerations in Energy Development*, Manila, May 1991) are typical in this respect: for example, the particulate emission coefficient for coal plants is given (on p.141) as 1-5 gm/kwh. There are vague references on the same page that ash contents range from 8-20%, and efficiencies from 30 to 37%. Nothing is said about what specific pollution control devices are presumed to be in place for the coefficient given.

[31] There is a second impact on CO_2 emission rates in the case of lime/limestone FGD systems (an effect also present in the case of fluidized bed combustion systems that use limestone as a sorbent). This follows from the fact that for every mole of SO_2 absorbed, one mole of CO_2 results (the essence of the entire set of very complicated chemical reactions being that calcium carbonate is transformed to calcium sulfate). These effects have the following impact on the CO_2 emission rate if we assume 80% removal of SO_2 in a lime/limestone based FGD system, a 1% sulfur coal, and a 5% degradation of heat rate. If the base rate of CO_2 emissions is 380Kg/10^6Kcal, then the heat rate degradation effect alone raises this to 399Kg/10^6Kcal, and the FGD system chemistry effect to 402Kg/10^6Kcal. Given the very high costs of CO_2 reducing emissions, even such small percentage changes should not be ignored.

[32] Central Bank of Sri Lanka, Annual Report, 1990; p. 1.

[33] Scrubbing exhaust gases to remove CO_2 is technically feasible, but extremely expensive, in excess of $200/ton of carbon. A variety of other exotic schemes have been proposed, including liquefaction and disposal in liquid form under high pressure at ocean depths of below 500ft (see e.g. M. Steinberg and H. Cheng, *A systems study for the removal, recovery and disposal of Carbon Dioxide from Fossil fuel power plants in the U.S*, Brookhaven National Laboratory, BNL 35666, July 1985). Such proposals are useful only as estimates of upper bounds.

[34] ICF, *Preliminary Technology Cost Estimates of Measures Available to reduce U.S. Greenhouse gas emissions by 2010*, Report to the U.S. Environmental Protection Agency, August 1990.

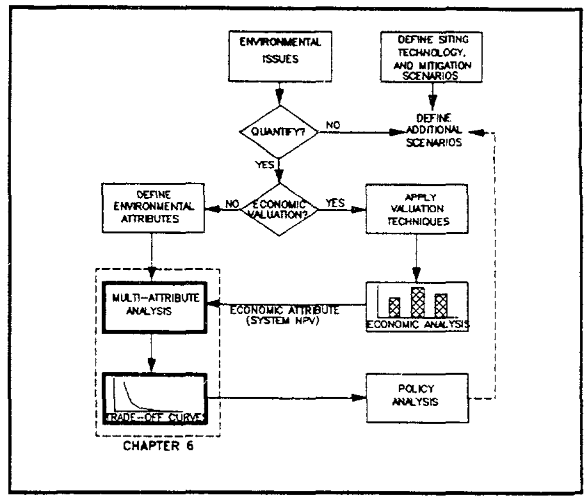
[35] In any event, emissions of GHGs from sources other than fossil fuel combustion are subject to considerable uncertainty. See e.g. C. Ebert and A. Karmali, *Uncertainty in Estimating Greenhouse Gas Emissions*, Work Bank Environment Department Working Paper 52, April 1992, Washington, DC. Several studies sponsored by UNEP, GEF, ADB and others are underway to improve basic information on natural and non-combustion sources of GHGs (for a review of such efforts, see e.g. J. Fuglestvedt *et al.*, A review of country case studies on climate change, Global Environment Facility Working Paper 7, Washington, DC, 1994.

[36] If we assume an inundated paddy area of 2000ha, then the equivalent CO_2 offset from reductions in methane releases would compute to:
2000 [ha] x 10000 [m^2/ha] x 1 [gm/m^2] x 100

[day/year] x 9 [CO_2/CH_4] x 50 [years]/ 1000 [gm/kg] / 1000 [kg/ton] = 900,000 tons of CO_2.

[37] This value does however fall very nicely into the range of one to twelve million dollars, which is the range of most estimates for human life for the US. The Pace University Study contains a good review of the US literature on health risk evaluation (Pace University, *op.cit.*, p.92-106). This review makes the very important distinction between the value of human life, and the value of *risks* to life: "..the economic value of health risks consist's either of society's willingness to pay to avoid risk, or willingness to be compensated to suffer the risk. The economic value of a health risk is not the value of a certain death, but the value of a risk shared by members of an exposed population" (p.92).

[38] However, this conclusion is for the high dam variant of the project, which has been rejected in favor of the run-of-river variant in the recently completed detailed feasibility study. It is likely that the feasibility study of the Upper Kotmale project, which consists of a large upper reservoir with potentially significant relocation impacts, and a smaller, run-of-river reservoir at Talawakelle will come to a similar conclusion, with the run-of-river project having only minimal relocation implications (However, as noted earlier, the lower reservoir has other environmental problems, such as the diversion of flow to the St. Clair falls).



6. MULTI-ATTRIBUTE ANALYSIS

We now come to a presentation of multi-attribute analysis: as discussed in Chapter 2, this is the centerpiece of the methodology used in this case study, for it enables us to deal with environmental impacts that cannot easily be economically valued. We present here only a very brief review of the principal ideas, since there are many excellent detailed texts.[1] We emphasize in this presentation the particular problems of applying these techniques to the integration of environmental considerations in power sector planning.

Introduction

Multi-attribute decision analysis has been developed expressly for situations where decisions must be made upon more than one objective which cannot be reduced to a single dimension. Its central focus is the quantification, display, and resolution of trade-offs that must be made when objectives conflict. In the case of application to the power sector, there may well be strategies that have beneficial impacts on environmental and on economic objectives -- most energy efficiency investments that are economically justifiable also bring about a reduction in emissions and hence improve environmental quality as well as economic efficiency. In most other cases, however, there are economic penalties associated with investments designed to reduce emissions and/or improve environmental quality. Thus the decision-maker must trade-off one objective against the other: lower costs means higher environmental impacts, and vice versa.

To be sure, to the extent that economic valuation of the environmental costs and benefits is possible, these might well outweigh the short run costs. However, from a practical standpoint, expressed in terms likely to be understood by laymen decision-makers, the trade-off is indeed one of short run economic costs (or the present value of readily quantifiable costs) against longer term benefits to environmental quality.

Multi-attribute decision analysis, even if not formally described as such, has in fact been used for some time for power plant siting and transmission corridor routing,[2] including in Sri Lanka itself. More recently, attempts have been made to use such techniques for broader studies of energy-environmental interactions, one application of which by the Asian Development Bank is discussed in the next Chapter. Finally, the technique has come into increasing use by state regulatory commissions in the United States in an attempt develop practical approaches to considering environmental objectives in the power sector.[3]

The application of multi-attribute methods involves the following steps:

1. Selection and definition of attributes, say A_i, $i=1, \dots N$, selected to reflect important planning objectives.

2. Quantification of the levels A_{ij} of the i attributes estimated for each of the j alternatives.

3. Scaling of attributes, in which the level of an attribute is translated into a measure of value, $v_i(A_{ij})$ (also known as the attribute

value function). This is sometimes combined with a normalization procedure (usually on a scale of zero to one where the lowest value of the attribute is assigned to zero, the highest attribute value assigned to one).

4. Selection of weights w_i for each attribute.
5. Determination and application of a decision rule, which amalgamates the information into a single overall value or ranking of the available options, or which reduces the number of options for further consideration to a smaller number of candidate plans.

While the steps appear conceptually straight forward, in general most applications give relatively little attention to a number of theoretical requirements for the results to be valid. In the following sections we discuss each of these steps in detail.

Selection of Attributes

Attributes, or measures of goodness, express the planning objectives to be considered in a given problem. Unfortunately, the need for care in the selection of attributes is not very evident from much of the literature of application of multi-attribute methods to power sector problems. Four main issues need to be addressed in the selection and definition of attributes:

Double counting: For example, there ought not to be a separate attribute for the miles of associated transmission line if there are already other attributes that capture the relevant land use impacts.

Value independence: Attributes (and criteria) should be conceptually distinct, i.e. preference independent.[4] Decision analysis differentiates between statistical independence and preferential independence; the former refers to the correlation structure of the alternatives, the latter to structure of the user's preferences -- a distinction that might be characterized as "facts" v. "values". Additive value functions -- such as those used in weighting and summation methods -- assume certain type of value independence, but statistical independence is irrelevant to the validity of the additive form.

A good illustration of the importance of value independence is illustrated by the poor criteria definition adopted by the New York State hazardous waste facility siting board, which established "danger of fire and explosion" and "population near site" as separate criteria to be added together. But these are not preferentially independent -- a high likelihood of explosion would motivate a user to put a higher weight on the criterion "population near site". One possible approach to avoiding this kind of problem is to define a new attribute as the product of the two.

Specificity: The rationale for selecting a particular attribute needs careful consideration. For example one frequently finds a criterion "solid waste disposal" expressed as tons of waste generated. Precisely why the quantity of solid waste is relevant is unclear, except that it is easy to estimate. Since a large part of the land required may be for solid waste disposal, there may in any event be double counting if there is also a criterion for "land use" (expressed in acres). Moreover, in fact the relevant environmental risk associated with ash and scrubber sludge disposal is the risk of toxic leachates contaminating nearby aquifers, which has very little relationship to the quantity of waste produced, but rather to characteristics such as soil permeability, depth to the groundwater table, and rainfall.

Proliferation of attributes: Many applications of multi-attribute methods suffer from the same malady that afflict environmental impact statements: in their desire to be comprehensive, they become tedious recitations of all possible impacts, with not much thought given to what is really important.[5] For example, in the scoring system used in testimony in a Vermont proceeding (which attempted to deal with the question of the relative environmental impacts of hydro imports from Canada, demand-side management measures, and decentralized renewable energy technologies[6]) 36 different attributes were used. These included separate attributes for each of the following material uses: steel, concrete, aluminium, silicon, glass, plastics and non-ferrous metals.[7] Exactly what environmental concerns the consumption of these materials implies that is not already reflected by other attributes is unclear.

A proliferation of attributes tends to make weighting more difficult (and may introduce a bias simply because one is reluctant to weight any particular attribute as near zero). Moreover, trade-offs become difficult to understand and display to decision-makers in comprehensible form if there are too many of them. The guiding principle ought to be that one starts from what are the most important impact issues (greenhouse gas emissions, health effects of fossil fuel pollution, the risk of groundwater contamination, the risk posed to aquatic ecosystems from thermal plumes, etc), and then select one attribute for each of these concerns.[8]

Care needs also to be given to making sure that attributes are appropriate to the scale of the problem. In this study, with its focus on system planning and national level environmental policy issues, it is important to exclude categories of impacts that are properly dealt with more effectively at the project level -- visual intrusion, noise, and so on -- and concentrate on those objectives that are substantively important to national scale policy-making.[9]

In selecting the attributes one might also bear in mind the following practical considerations:

1. are the attributes sufficiently predictable, at reasonable effort and cost, at the system planning level?
2. are the attributes important enough to affect the generation mix-policy choice decision?

Quantification

In some sense, obviously, the definition and quantification of attributes goes hand in hand: non-quantifiable attributes are generally of little value. To be sure, in some cases, indirect valuation methods can be used without direct quantification: for example, some of the hedonic pricing methods can be used to estimate the impact of a power facility -- say by examining property prices in the vicinity of a large generating facility -- without necessarily having to quantify the actual impact such as incremental air pollution (at a fossil plant) or incremental radiation or probability of catastrophic accident (at a nuclear plant).

One of the important issues is to be sure that what is quantified is as closely related to impact as possible. Thus, rather than focus on measures related to regulatory convenience, we focus on a measure demonstrably linked to actual impacts. In this case study, for example, instead of using emissions or ambient air quality changes as the relevant air pollution attribute, we use population weighted exposure to ambient concentration of air pollutants as the measure of health impact damage.

Scaling

Whenever possible, it is desirable to work with value or utility functions rather than purely physical scales for attribute measurement: this transformation is known as scaling. In the example of Figure 6.1 we show alternative representations of a scaling rule for aquatic ecosystem damage. The simplest representation (attribute value function 1) is a simple linear scale that has the implication, for example, that a 1 degree rise in temperature from 26 to 27 °C produces the same damage as a 1 degree rise from 29 to 30 °C. Attribute value function 2, on the other hand, implies a non-linear relationship between some measurable physical characteristic and environmental damage. Indeed, this particular type of function implies the existence of a threshold beyond which impacts become more severe.

Weighting

How the weights are determined is obviously a crucial step, and experiments that have been conducted in applications to power plant siting and water resource planning problems show that which method is used to choose weights can significantly affect the outcome.[10] It has been demonstrated by a number of decision scientists and psychologists[11] that weights based upon vague statements of importance (such as "economy and environment are equally important") may have little to do with preferences of users for trade-offs among criteria

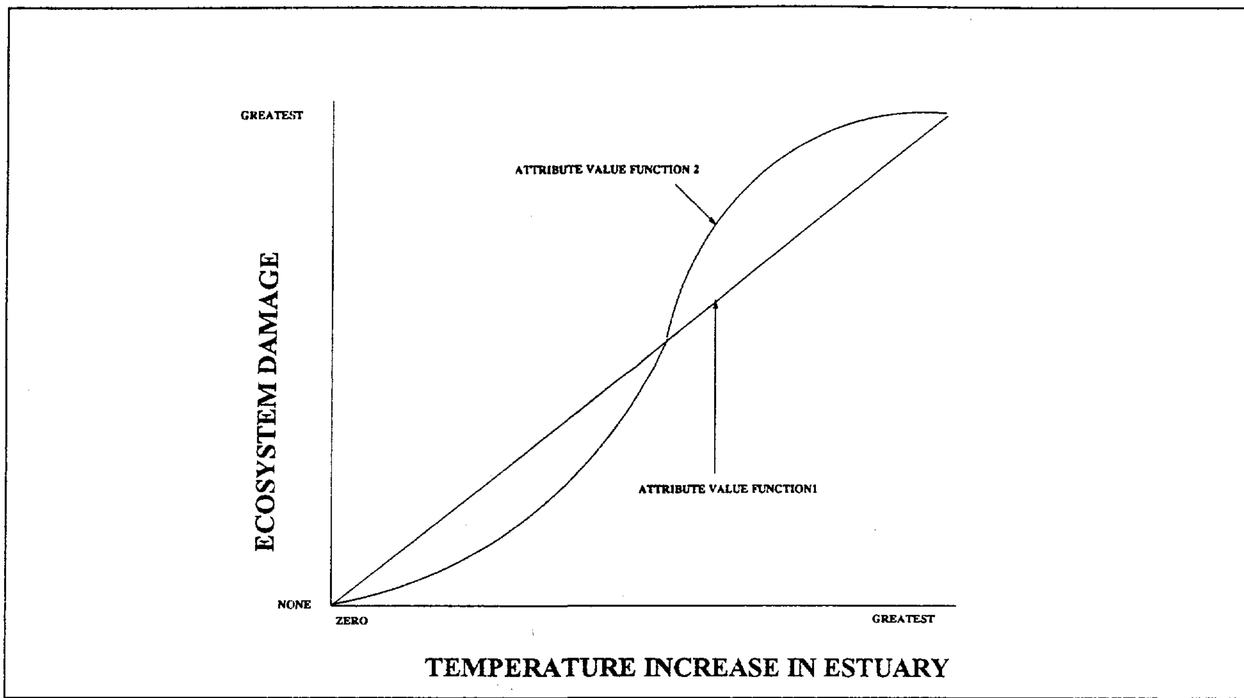


Figure 6.1: Attribute scaling

(e.g. what increase in power costs can be tolerated in exchange for a 10% reduction in CO_2 emissions). Thus the most commonly used method, rating on a 0-5 or 0-100 scale, is likely to be invalid in most applications, as the ratings a person chooses may have little to do with the trade-offs he or she is willing to make among the criteria. It is for this reason that in this study of Sri Lanka we place such emphasis upon the generation and display of the trade-off curves, which is the fundamental first step in multi-criteria analysis, rather than on weighting.

Decision rules

A great many decision rules have been developed and applied in the literature of multi-attribute analysis, and a complete review goes beyond the scope of this report,[12] We discuss here only those that are most relevant to power sector applications.

Exclusionary screening

Exclusionary screening is often used to define one or more candidate areas in a power plant siting study. This is a decision rule in which candidates are rejected if at least one attribute falls below some pre-defined standard. In the example below (Figure 6.2) the areas above the standard for attribute A_1, and to the right of attribute A_2, are unacceptable: this leaves as the acceptable region the pie-shaped slice as indicated.

Exclusionary screening needs to be conducted with great care.[13] The problems are well illustrated by the experience of the first studies for a coal-fired power plant in Sri Lanka. Sites in the south were never explored in any great detail, largely on grounds that lacking deep-water harbors, the cost of coal shipment in smaller vessels was thought to be prohibitive, and not justifiable economically. Such reasoning inevitably led to the choice of Trincomalee (in the northeast) as the optimal siting area. In effect, the screen applied was the immediate proximity of a deepwater port.

Yet once the environmental problems at the Trincomalee site became evident, the south coast was considered for a site after all -- although consideration of a site in the Matara area was also subsequently suspended.[14]

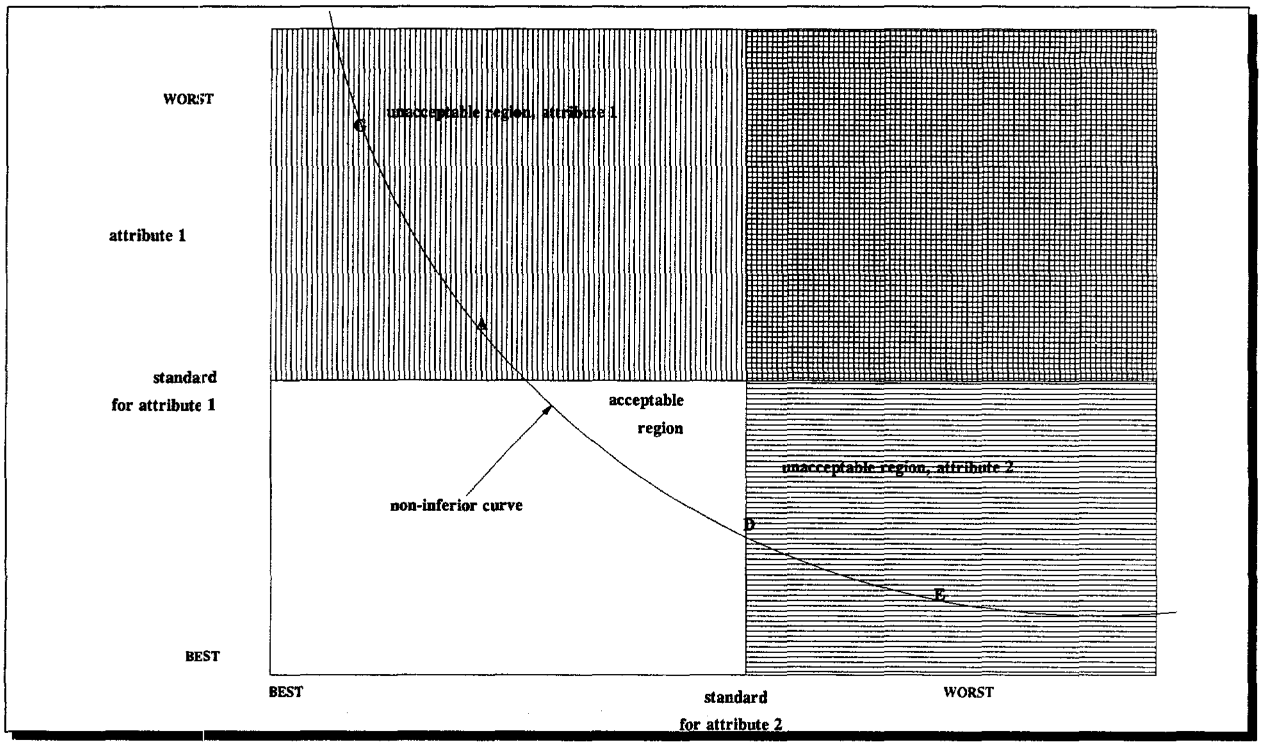


Figure 6.2: Exclusionary screening

Subsequently, another implicit screen was applied (although not recognized as such). Having once chosen the Trincomalee Bay siting area, only once-through cooled plants with discharge near the coastline were considered. This is equivalent to screening out, a priori, a whole host of other technology and mitigation options, with the rationale that these need not be considered because once-through discharges would likely meet the only standard that was thought to apply.[15] All six sites considered in detail were once-through cooled discharging into well-mixed shallow bay waters.

When the environmental impacts of this cooling mode were deemed unacceptable, the entire concept of a Trincomalee Bay site was also rejected. Yet what should have been done was to also examine other cooling modes: it would have been much harder to characterize the impacts of once-through cooling as "negligible" if the comparison had been to a system with cooling towers, or to a system involving discharge to deeper bay waters.

Indeed, exclusionary screening may not have much value in many developing countries, except for the most obvious requirements. For instance, in Sri Lanka, there is clearly no need to examine a 1,000Mw coal burning power plant in the hill country. Only where there exist strict regulatory requirements, known to be rigidly enforced (e.g. no facilities may be built in designated wildlife sanctuaries), or technology specific site requirements (e.g. no nuclear plants in areas containing geological faults) can one apply such environmental screening with confidence. The important lesson of the initial Trincomalee site screening analysis is to avoid the use of inappropriate screens; and indeed in the subsequent "Thermal Options" study, a much wider set of sites was examined.

Weighting summation

The weighting summation method is a widely used decision rule in environmental analysis and power plant siting. It selects that option that has the highest score

$$\sum_i w_i V_i(A_i)$$

where w_i is the weight, and $V_i(A_i)$ is the value function of attribute A_i.

This procedure, employed widely in the United States, has come into use in developing countries over the past decade as well. It was also the basis for site selection recommendations in the various Black and Veatch power plant siting studies conducted in Sri Lanka in the 1980s.[16]

Nevertheless, although the approach is widely used, many applications appear to show little respect for the theoretical requirements for the method to be valid, and for the results to be reliable. The most important of these requirements are that the attributes are independent (to avoid, among other things, unintended double counting), that the value functions may not be ordinal (to avoid violating fundamental principles of measurement theory), and that attribute scales must be normalized (to ensure independence of weights from value scales).

In an analysis performed for the U.S. Nuclear Regulatory Commission,[17] widespread deficiencies were determined in the application of site selection models. None of the studies acknowledged the existence of theoretical requirements. At least 5 of the site selection studies incorporated algebraic manipulation of ordinal measures. Ten of 13 applications of the weighting summation method violated theoretical requirements of measurement theory (such as algebraic manipulation of ordinal numbers), and 8 of 13 violated the assumption of attribute independence.

Candidate option screening

The decision criterion used as the centerpiece of this study can be defined as "candidate option screening". The intent is to identify, from what is generally a very large set of alternatives, those that merit further consideration by the decision-makers. This generally means the identification of some small number of plans that can be shown to be superior to all others, but which involve some explicit trade-off.

Let the universe of initial options be denoted P_1, P_2, etc. Suppose for the sake of clarity that there are only two attributes: cost, and an environmental attribute reflecting the population exposure to SO_2. Figure 6.3 depicts the solution space for this problem, in which we plot the values of the two attributes for each plan.

The plan P_1 is said to strictly dominate plan P_2 if P_1 is better than (or equal to) -- i.e. dominates -- P_2 in terms of every attribute, and

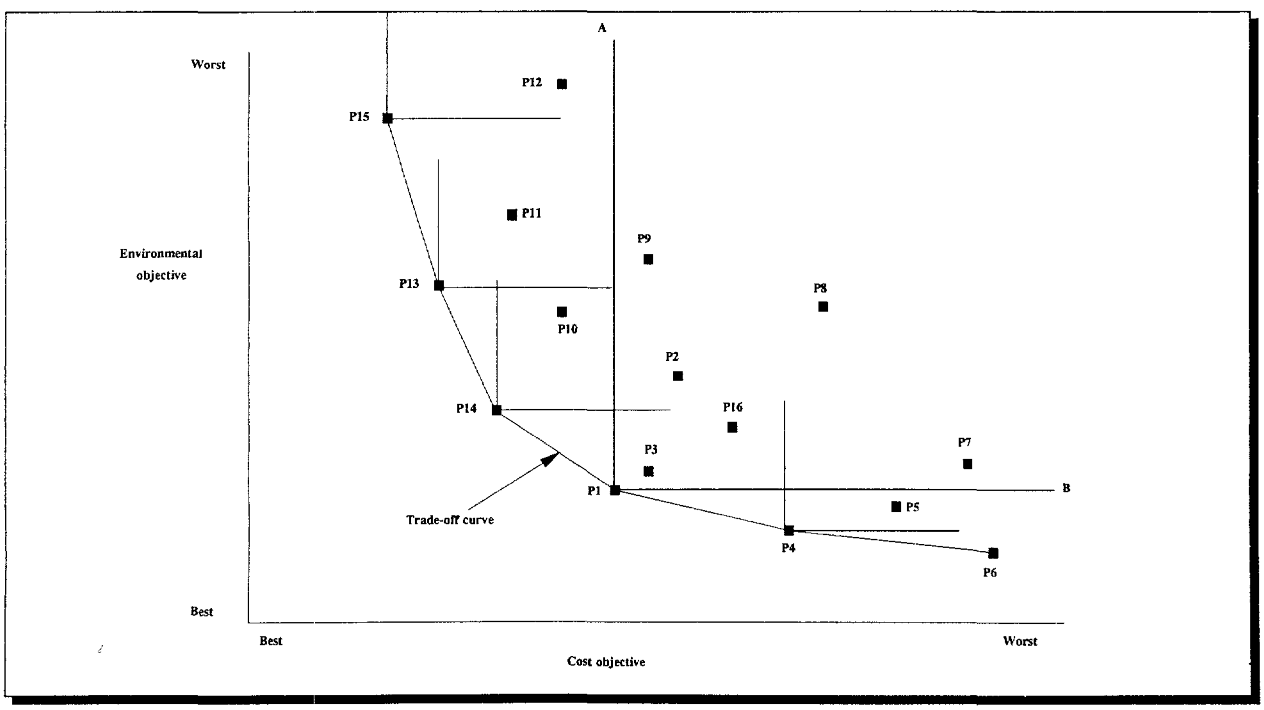


Figure 6.3: The two-attribute problem

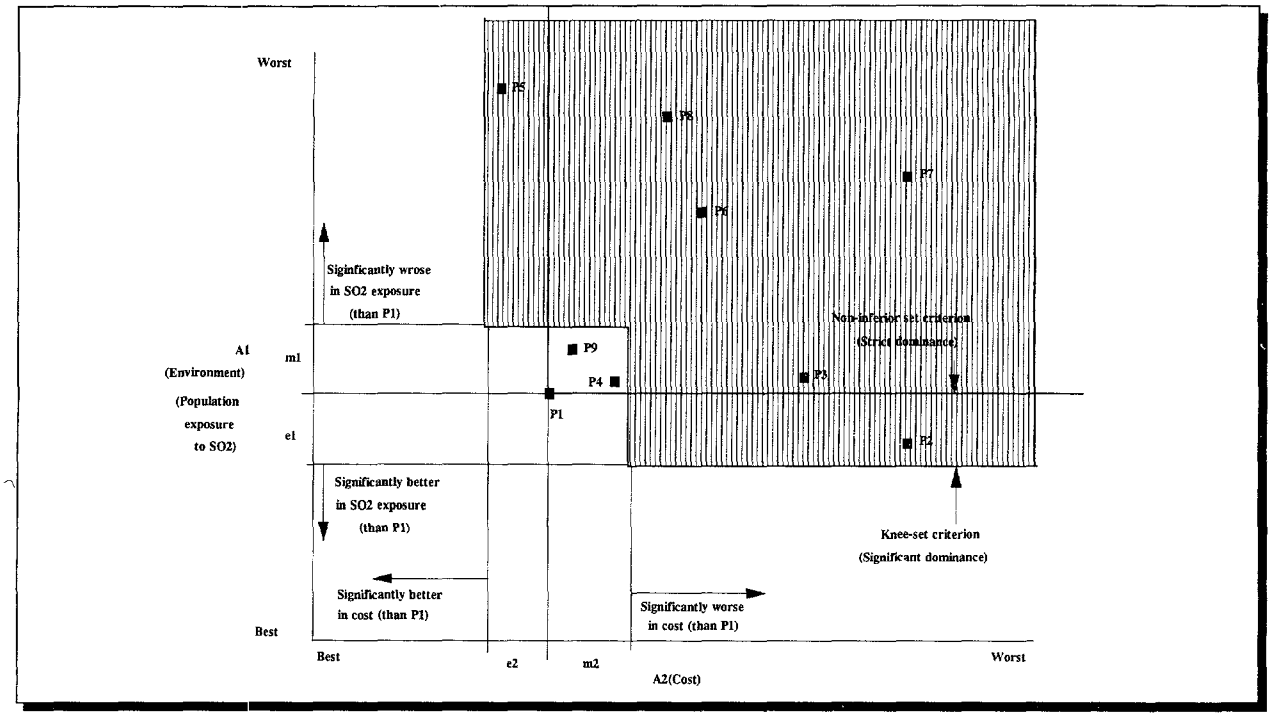


Figure 6.4: Significant dominance

is strictly better in at least one attribute. Thus, as illustrated on Figure 6.3, P_1 is better than P_2 in both cost and SO_2 exposure. In fact, P_1 strictly dominates all of the plans northeast of the boundary AP_1B. By repeating such comparisons for all pairs of plans, and discarding all dominated plans, the remaining plans constitute the set of the so-called non-inferior solutions -- in our case the set of plans $\{P_6, P_4, P_1, P_{14}, P_{13}, P_{15}\}$.[18] These points in turn define a trade-off or non-inferior curve, as indicated on Figure 6.3.

This procedure will in general provide a means for reducing a very large number of possible plans to some smaller number of plans -- a "short-list" or "candidate list" that is to be presented to decision-makers. In the example shown, using the concept of strict dominance, plan P_3 would not appear on the resulting short list. Yet one might argue that while P_3 is somewhat worse in both attributes than P_1, it is not significantly worse, (as opposed to, say, P_4 and P_8, which are significantly worse in both attributes). In particular, because of uncertainties associated with the calculations, one may be reluctant to discard a plan that is not significantly worse than another from a final short-list, (especially if such an option involves a generation or demand side measure not included in the other plan).

This idea is captured by the concept of significant dominance.[19] P_1 is said to significantly dominate P_2 if $A_i(P_1) + m_i < A_i(P_2)$ for at least one i, and if $A_i(P_1) - e_i < A_i(P_2)$ for all i, where m and e are significance parameters or tolerances. m_i is the smallest difference in values for attribute A_i such that one plan is considered to be much worse than the other, and ei is the largest difference between values such that one plant is considered equivalent to one another.[20]

These concepts are illustrated on Figure 6.4. P_1 significantly dominates all of the plans in the shaded region. Note that P_2, which is not *strictly* dominated by P_1, is *significantly* dominated. That is, significant dominance also rejects solutions where the improvement in one attribute (in this case in the environmental objective) is bought at great cost in the other (in this case in cost). In other words, from the environmental perspective, for a plan to be

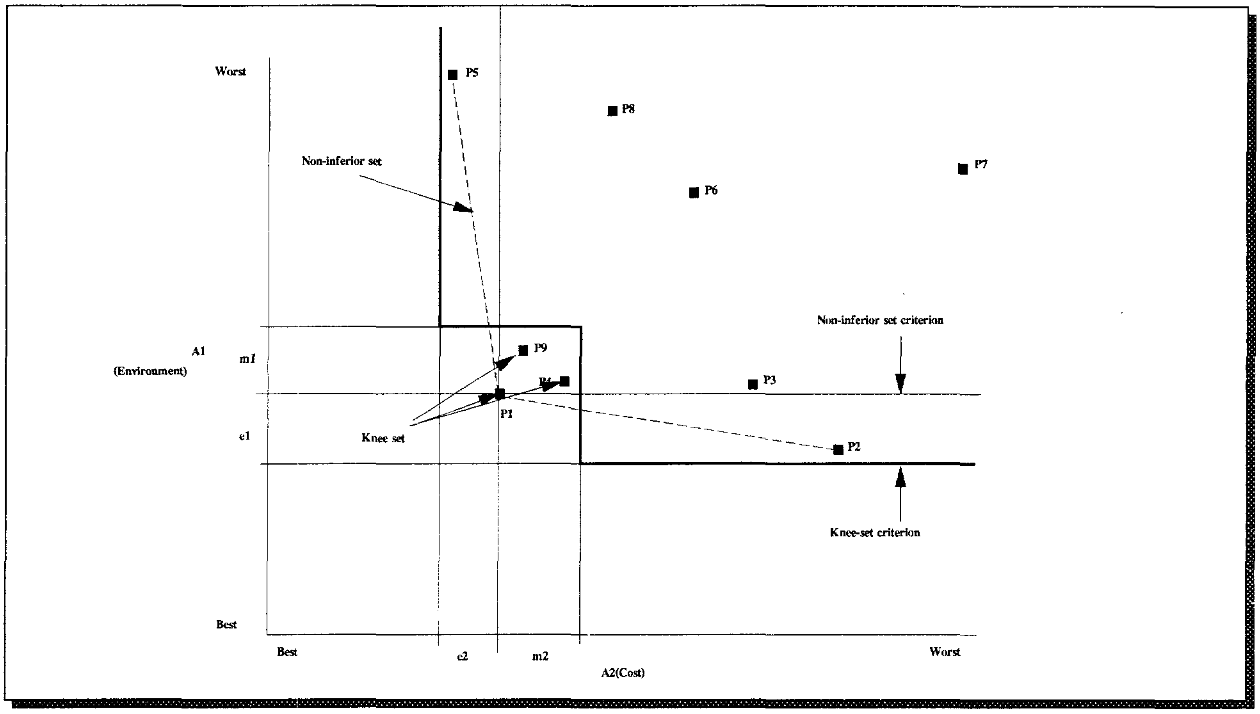


Figure 6.5: Knee set definition

significantly better than P_1, it must have a value less than $P_1 - e_i$.

The so-called <u>knee set</u> is the set of plans which are not significantly dominated. In the example of Figure 6.4, redrawn on Figure 6.5, the knee set is $\{P_1, P_4, P_9\}$. Note that this set differs from the non-inferior set, defined by the trade-off curve, which is the set $\{P_2, P_1, P_5\}$. From the practical standpoint of decision-making, the knee set is clearly the more useful, since the non-inferior set also includes solutions where slight improvements in one objective are bought only at great cost in the other -- such as P_5 and P_2. Another way of expressing this is that the knee set consists of that set of plans for which decision-makers representing different objectives are most likely to agree upon. In the above example, for example, both P_5 and P_2 are unlikely candidates for agreement, even though both lie on the trade-off curve.

Obviously the knee set will be a function both of the values of the significance parameters used, as well as the shape of the trade-off curve. In the situation of Figure 6.5, the knee set is relatively compact, because the trade-off curve exhibits a sharp rate of change of curvature at P_1. However, in the situation shown on Figure 6.6, there are no sharp changes in curvature of the trade-off curve: here the knee set is the same as the non-inferior set.

All of the mathematical definitions of knee sets and non-inferior sets continue to be valid when there are more than two dimensions. In this case, one should properly refer to the trade-off surface, say $S = S(C, A_1, A_2, \ldots A_n)$, which is a n-dimensional non-inferior hyper-surface, where C is the cost attribute, and A_i $(i=1,..n)$ are n environmental attributes.

A rigorous definition of the trade-off between any two of these attributes would require that the values of all of the others are held constant. In practice that is rarely possible -- for example, finding a series of plans that all had the same water impact, but varied only in cost and air quality impact would be hard to find. What can be done is to simply plot the values of two attributes (e.g. C versus A_1), and to assume that the variations in the other attributes may be ignored. In other words, in the three-dimensional case, the third dimension is in effect projected onto the two-dimensional

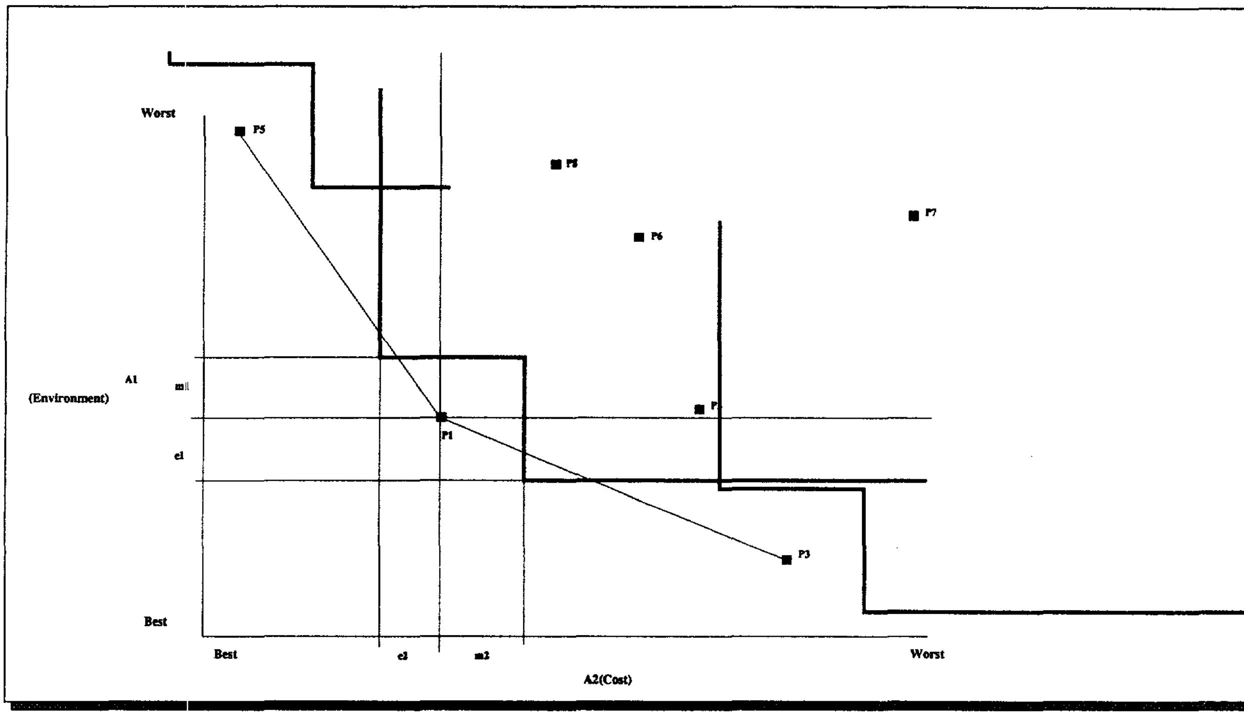


Figure 6.6: Knee-set equivalent to the non-inferior set

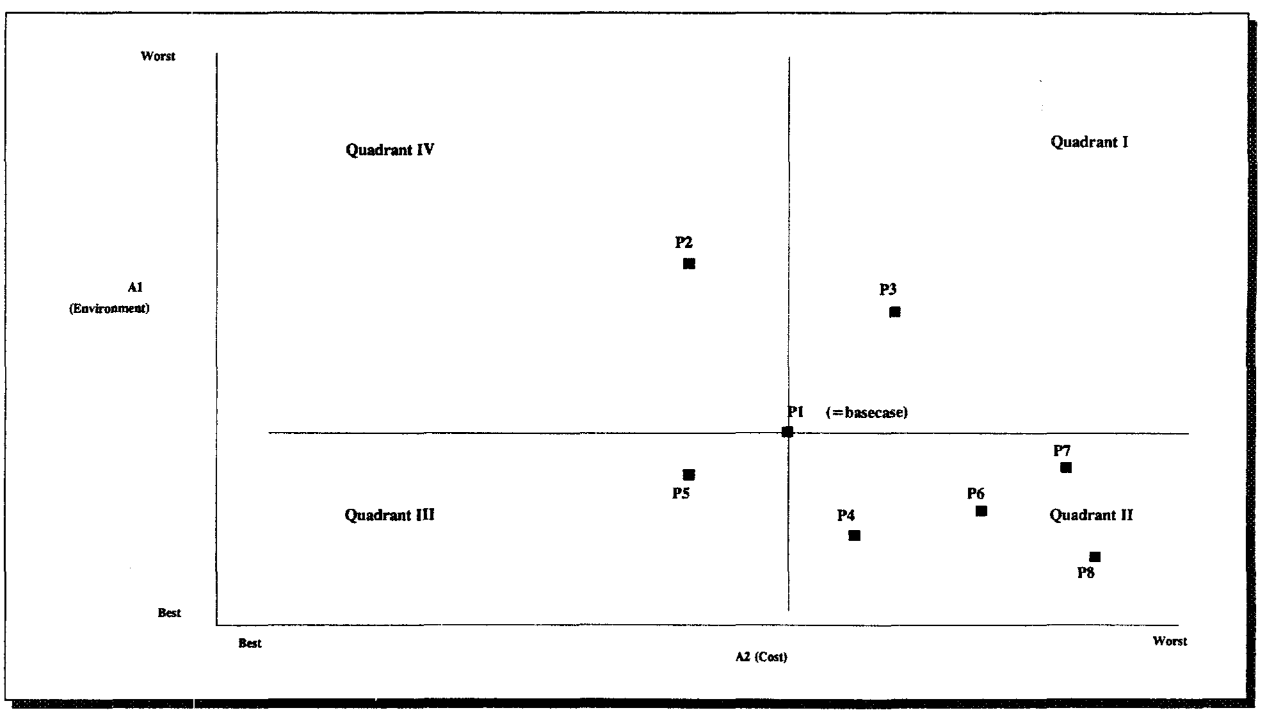


Figure 6.7: The quadrant criterion

plane of the two attributes being displayed, ignoring variations in the third dimension.[21]

Indeed, while looking at attributes only two at a time does provide great insight, it may not in fact reveal all of the members of the non-inferior set. This importnat point is illustrated in the Annex I.

Finally, also useful is the so-called quadrant criterion (see Figure 6.7), which involves the comparison of selected options with respect to the basecase, located at the origin. Plans that lie in the quadrant III are better than the basecase on both criteria,[22] while those in quadrant I are worse than the basecase on both criteria: in these cases there are no trade-offs to be made, because both interests (i.e. both economic efficiency and environment) are served in adopting options in quadrant III, and both are served by avoiding options in quadrant I. It is in quadrants II and IV where trade-offs must be made -- where an improvement in one objective necessarily implies a worsening in the other.

Annex I:

The three-dimensional case

As an illustration of the caution that needs to be applied when looking only at the two-dimensional representations of the trade-off surface, consider a three-attribute example with attribute values for five plans as shown on Table 6.1.[23] The two-dimensional plots are shown on Figure 6.8.

Table 6.1 : a three-dimensional example

	cost	air	water
a	0.50	0.10	0.95
b	1.00	0.50	0.10
c	0.10	0.90	0.50
d	0.60	0.60	0.60
g	0.70	0.35	0.95

From Figure 6.8 one might infer that the non-inferior set is {a,b,c}, since in two dimensions the members of the trade-off curve are {a,b} for water versus air; {c,b} for water versus cost, and {a,c} for air versus cost. Both d and g appear to be strictly dominated.

But as inspection of Table 6.1 shows, in fact when one uses the mathematical definition of strict dominance in a simultaneous comparison of all three attributes, only g is seen to be strictly dominated (by a). Option d is seen to be preferred over b in cost, preferred over c in air, and over a in water. Indeed, it may in fact be an attractive compromise solution to decision-makers representing different interests because it avoids very bad outcomes.

For example, from the environmental perspective one may accept a second best outcome for, say, water, if one can avoid the worst case outcome for air quality. Such a preference behavior on the part of decision-makers can be captured by an asymmetrical definition of the tolerance parameters in the knee-set definition: if $e >> m$ (see Figure 6.3), then it quickly follows by inspection from the above table that d is the only member of the knee set! For example, if e_i=0.5, and m_i=0.1, then because a is no longer significantly better than d for the air quality criterion, but is significantly worse than d for water, d significantly dominates a, and so on.

None of this invalidates the two-dimensional plots of the trade-off surface: it still provides a view of those plans that are closest to the origin (i.e. best) for the two attributes displayed. However, it must simply be recognized that both knee-set and non-inferior sets must be defined on the basis of the simultaneous, multi-attribute inspection of attribute values: looking only at the two-dimensional displays may not uncover all of the solutions of actual interest to decision-makers.[24]

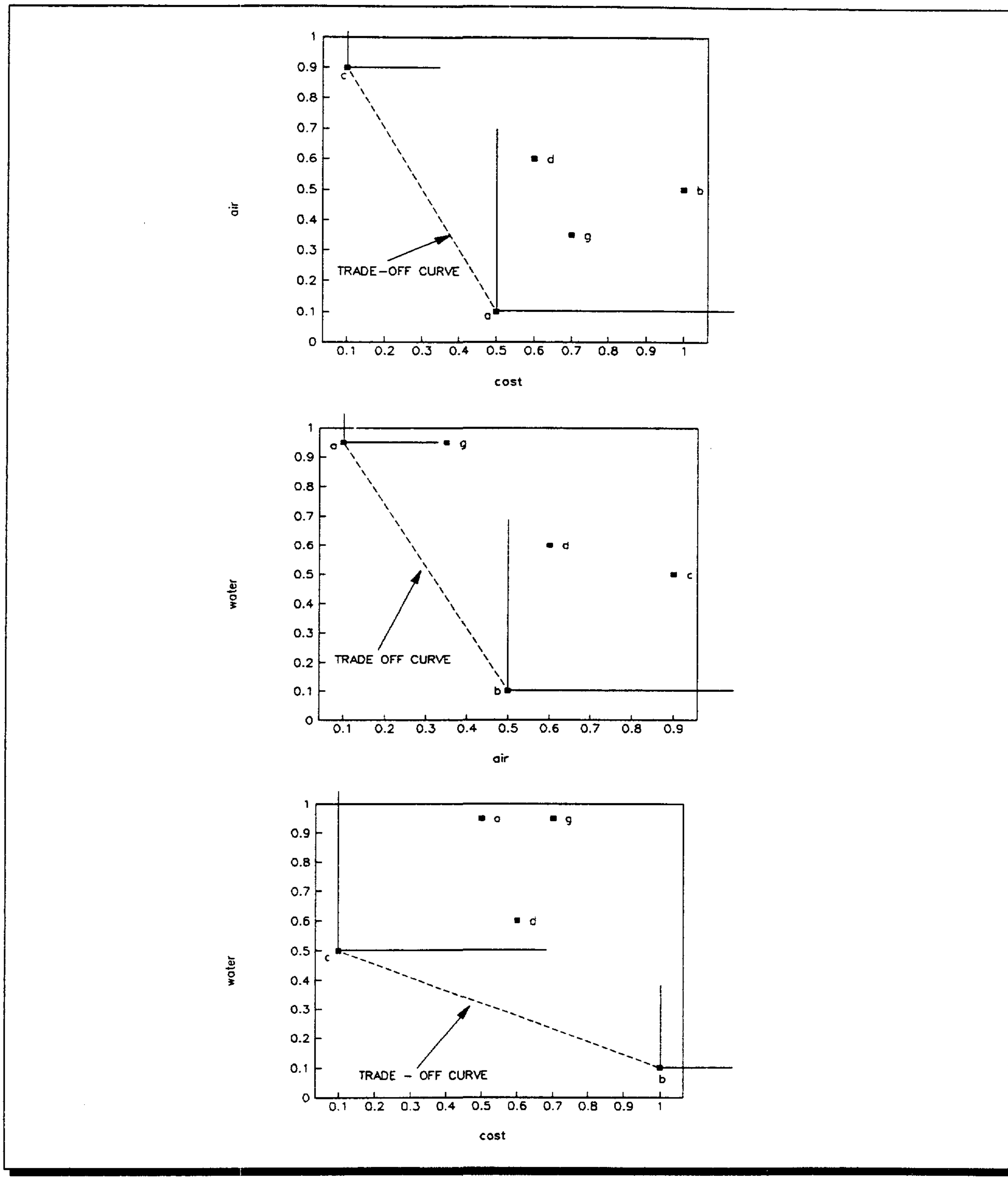


Figure 6.8: A three-dimensional example

Annex II:

Generating trade-off curves

Although a review of the literature reveals a great many different approaches to the problem of identifying the non-inferior set, three methods account for the bulk of practical applications. The first two, the so-called constraint method, and the weighting method, are derived from the theory and practice of multi-objective mathematical programming (Cohon 1978); the third is simply to generate the solution space of discretely defined plan alternatives in a simulation model, and determine the trade-off curve and knee set by inspection-- as described earlier in the Chapter[25].

In the constraint method, one solves a series of optimization problems of the type

Min COST

subject to $SO_2 < SO_2(max)_i$

for a series of different values of $SO_2(max)_i$.

The principle is illustrated on Figure 6.9. One first minimizes cost subject to $SO_2 < SO_2(max)_1$, for which the minimum cost plan is clearly P_9. Then one tightens the SO_2 constraint to $SO_2(max)_2$ (defined as $SO_2(max)_1 - \Delta$), for which the least cost solution is P_5. In this way, by successive tightening of the SO_2 constraint, the non-inferior set $\{P_9, P_5, P_{10}\}$ is generated.

In practice, this method has its hazards: as one can see from Figure 6.9, the points P_1 and P_3 have been missed, given the way in which the successive $SO_2(max)$ constraints have been defined. There are two ways of getting around this problem: the first is to make the Δ value very small, so that the probability of missing a point such as P_3 is minimized. For example, with Δ set at half the previous value, as indicated on Figure 6.10, P_1 enters the non-

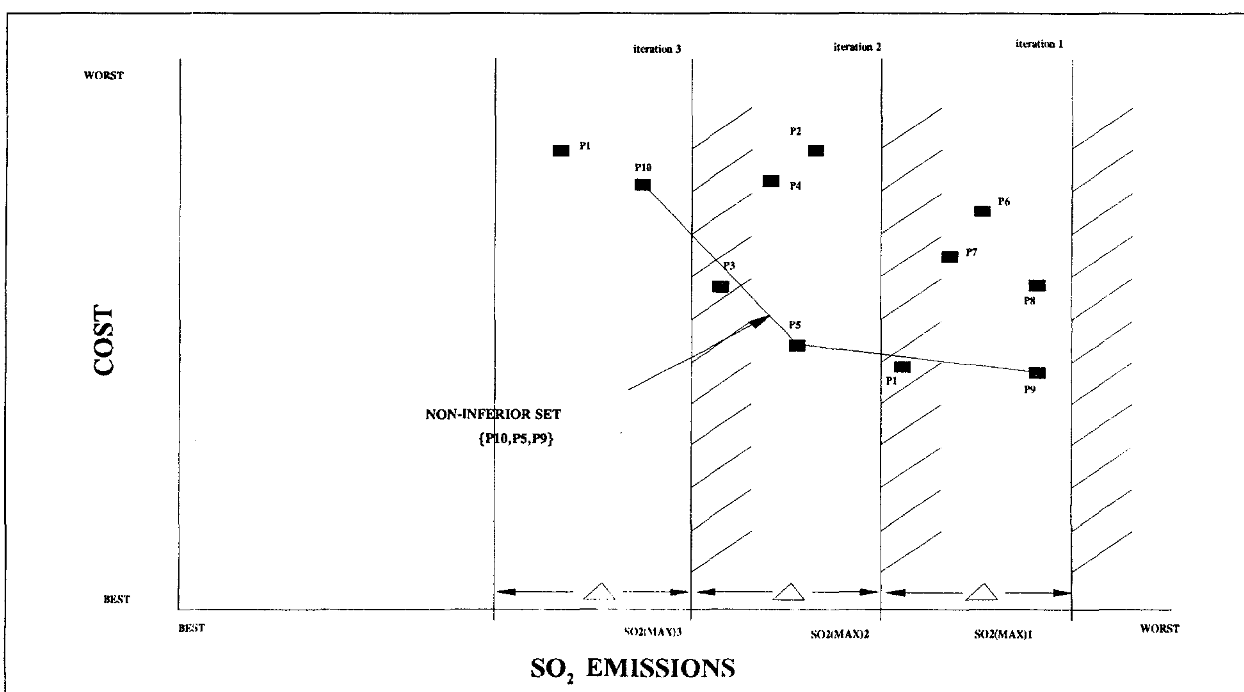


Figure 6.9: The constraint method

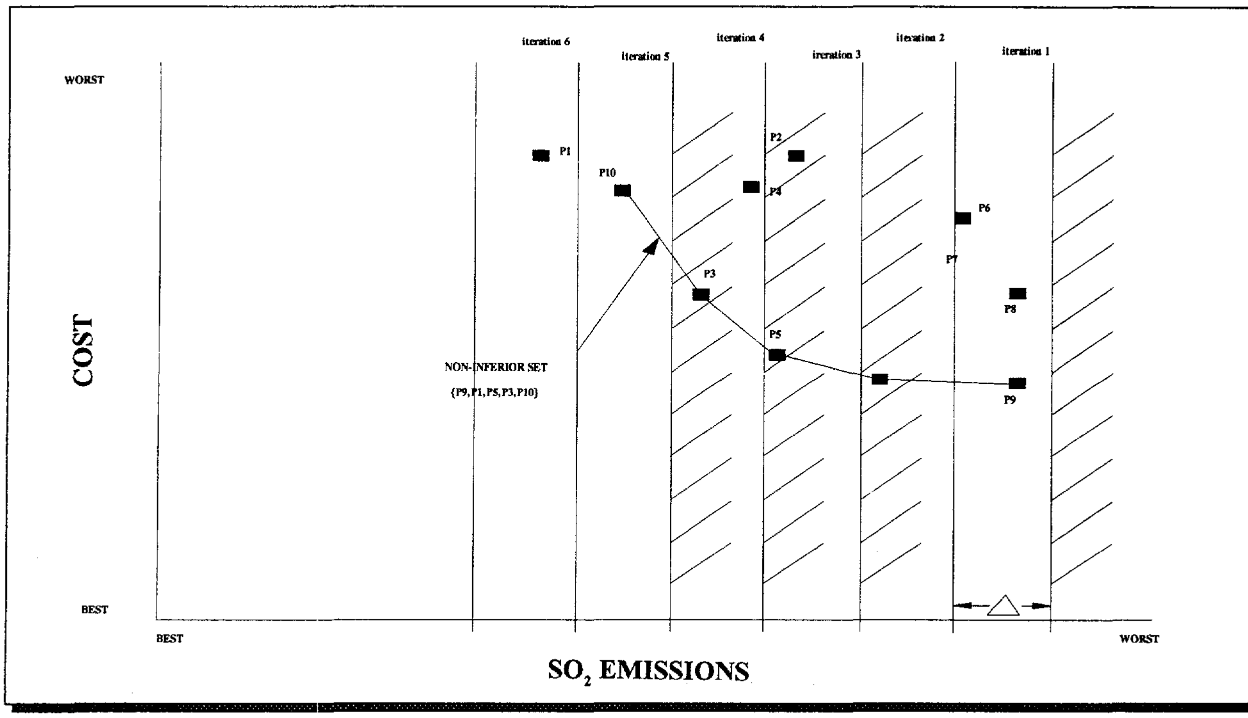


Figure 6.10: constraint definition

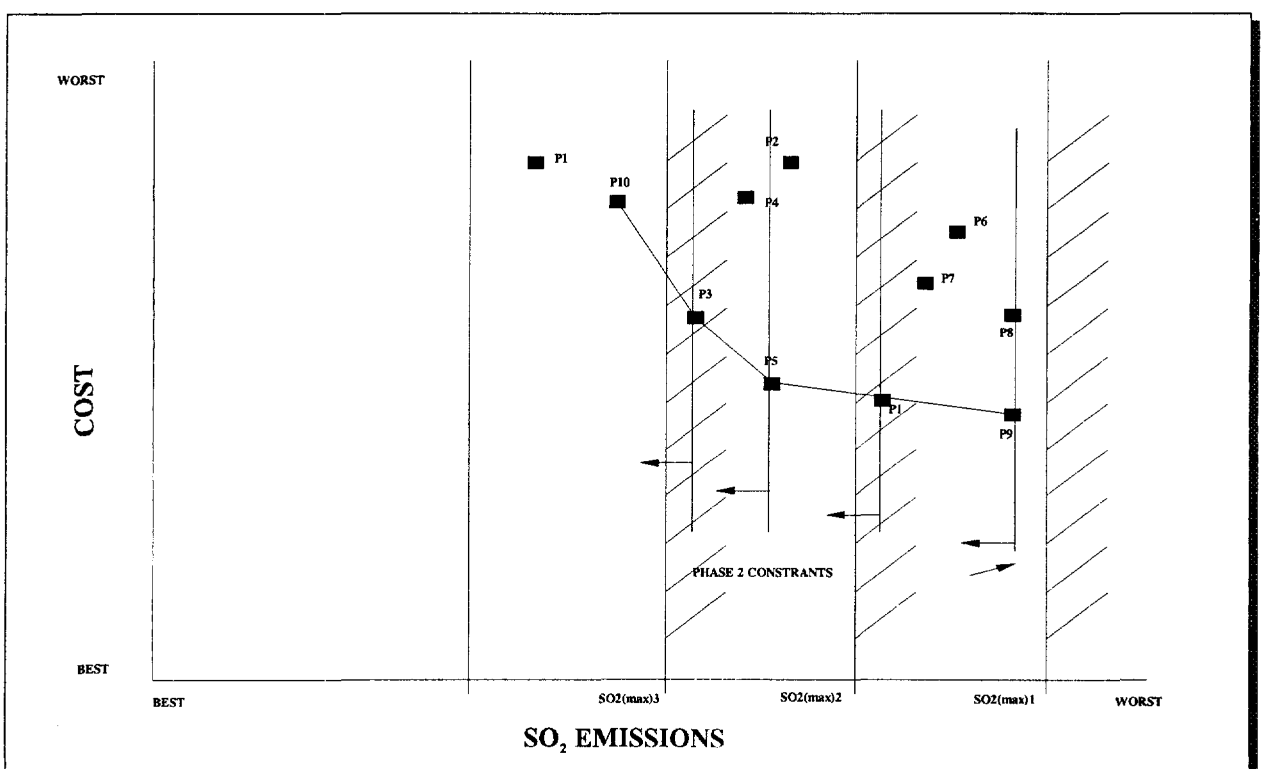


Figure 6.11: Confirming the non-inferior set

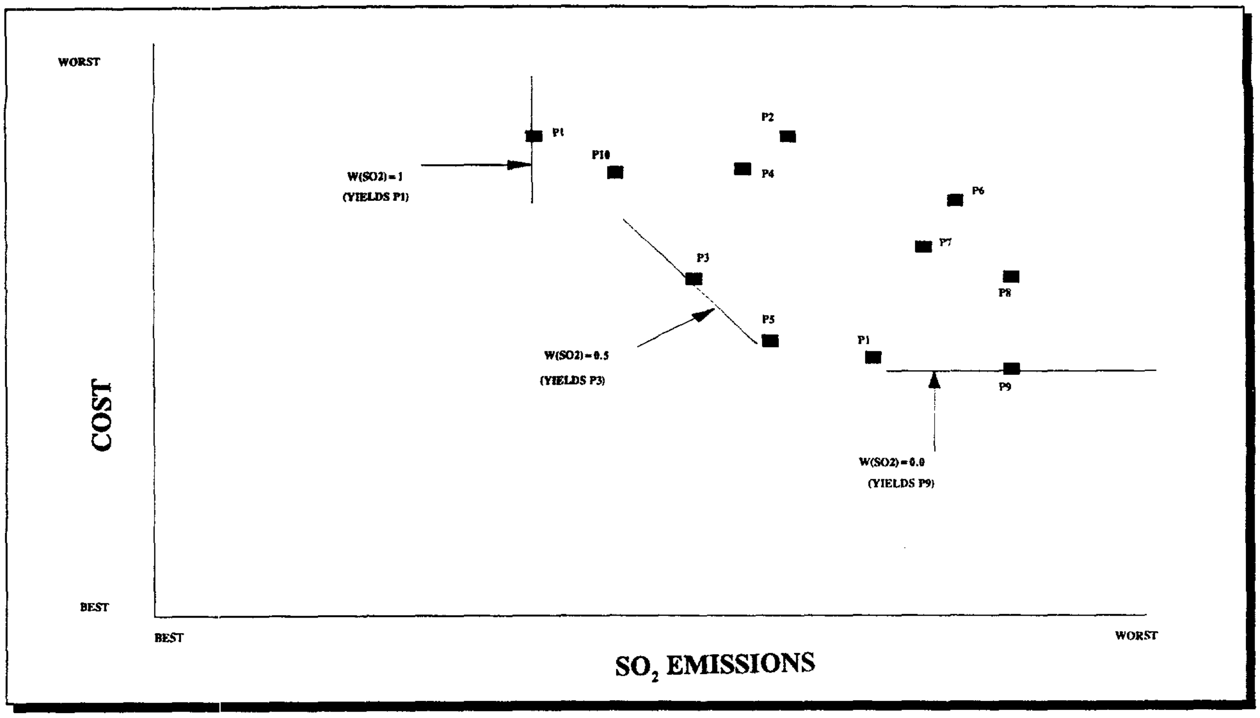


Figure 6.12: The weighting method

inferior set at the second iteration, and P_3 at the 4-th iteration.

A second way of confirming the completeness of the non-inferior set is in a two-phase procedure. In the first phase, one determines the non-inferior set, as described above. In the second phase, one reruns a series of optimizations using the SO_2 values of the initially defined non-inferior set step as the constraints. Thus, in phase two, the first optimization is subject to the constraint

$$SO_2 < SO_2(max)_1 - \delta$$

where δ is some very small increment. This optimization yields P_9, already identified as being in the non-inferior set. Next one reruns the optimization subject to

$$SO_2 < SO_2(P_9) - \delta$$

which now yields P_1, the previously unrevealed member of the non-inferior set. P_1 is added to the non-inferior set, and the process continues with the next optimization subject to

$$SO_2 < SO_2(P_1) - \delta$$

which will reveal P_5 as the next member of the non-inferior set. This procedure will ultimately reveal the correct non-inferior set $\{P_9, P_1, P_5, P_3, P_{10}\}$

The weighting method solves a mathematical programming problem of the type

$$Min(1 - W(SO_2))\ COST + W(SO_2)\ SO_2$$

over a range of values of $W(SO_2)$. When $W(SO_2)=0$, the result is the least cost solution. When $W(SO_2)=1$, the result yields that feasible solution that minimizes SO_2 emissions (which in practice might be an all hydro generation plan). Intermediate values imply different slopes, and, as indicated on Figure 6.20, will yield intermediate points of the trade-off curve. The model by Amagai and Leung (1991) (see Chapter 7), used a procedure of this type to generate the trade-off curve between cost and CO_2 emissions in Japan.

Notes

[1] One of the best detailed presentations, that has direct relevance in its focus on power plant siting, is B. Hobbs, *Analytical multi-objective decision methods for power plant siting*, US Nuclear Regulatory Commission, Report NUREG/CR-1687, August 1979. The classic text on the subject is R. L. Keeney and H. Raiffa *Decisions with multiple objectives: preference and value trade-offs*, Wiley, New York, 1976.

[2] It is hard to evaluate whether cases in which formal models were used for siting decisions were any better than in cases in which they were not. It is certainly true that the most celebrated siting controversies in the United States, from the Storm King Mountain pumped storage project to the Shoreham and Seabrook nuclear plants, would not have been resolved sooner, or at less cost to the economy, had formal siting models been applied. But these siting decisions were in fact made in the 1960s, and the use of formal siting models was significantly improved in the 1970s as a direct consequence of the problems encountered at these (and other) plants. The most important lesson from the application of formal siting models in the United States is the need for public participation in the decision process: it was very quickly realized that as decision models forced explicit quantification of values and preferences, this could no longer be done by the self-appointed "siting experts" of the utilities and their consultants.

[3] For a discussion of the potential of multi-criteria methods in developing country water resource projects, see e.g. Assessment of multiple objective water resources projects: approaches for developing countries, United Nations Environment Programme, United Nations, New York, 1988.

[4] A set of attributes $\{X_1, X_2, .. X_n\}$ is preference independent of its complement (i.e. the other attributes $\{X_{n+1}, X_{n+2},..X_N\}$) if the trade-offs a decision maker is willing to make among the $\{X_1, X_2, .. X_n\}$ do not depend upon the levels of its complement.

[5] This was a major problem in the United States in the early years of NEPA. In 1977, in response to EISs of increasingly encyclopaedic proportions, President Carter directed the Council on Environmental Quality, the entity established to monitor NEPA, to issue new regulations "...designed to make the EIS more useful to decision-makers and the public; and to reduce paperwork and the accumulation of extraneous background data in order to emphasize the need to focus on real environmental issues and alternatives " (Executive Order, May 24, 1977). This led to the development of the so-called scoping process as a means to direct effort to real problems.

[6] I. Mintzer, *et al.*, *Environmental Externality Data For Energy Technologies*, Center for Global Change, University of Maryland, July 1990.

[7] This study also proposed an interesting approach to the determination of weights, based on the reversibility of the impact as the most important factor: high level radioactive waste from a nuclear power plant would be assigned a high weight because it remains radioactive for thousands of years; while thermal pollution of a river during low flow periods would be assigned a low weight. However, what is critical to validity is whether or not the weights actually reflect the trade-offs that decision makers would actually be prepared to make in practice.

[8] All these points have long been established in the decision sciences literature, and were validated in a large number of applications in the 1970's to power plant siting particularly by Keeney and his colleagues (see e.g. Keeney, R. L. and H. Raiffa, *Decisions with Multiple Objectives: Preferences and Value Trade-offs*, New York: Wiley, 1976; and Keeney, R.L. and K. Nair, Nuclear Siting Using Decision Analysis, Energy Policy, 5, 3, 223-231, 1977). The 1981 EPRI report by Woodward-Clyde (1981) is one illustration of a well-founded application of decision theory to utility resource planning (a coal/nuclear choice).

[9] Such judgements are sometimes quite difficult to make in practice. For example, the Upper Kotmale project would divert the Kotmale Oya into a power tunnel at Talawakelle, resulting in the loss of the St. Clair's waterfall a few miles downstream. While this is a highly site-specific impact, the falls are nationally renowned, and a significant tourist attraction, and their potential loss would inevitably cause intense public controversy. The site specific mitigation measures -- such as maintaining some minimal downstream flow -would not only be expensive in terms of lost power benefits, but are

certainly within the scope of a national level planning study in this instance.

[10] see e.g. B. Hobbs, A comparison of weighting methods in power plant siting, Decision Sciences, 11, pp. 725-37, 1990; or B. Hobbs, Does choice of multicriteria method matter: an experiment in water resource planning, Water Resources Research, July 92.

[11] see e.g. Von Winterfeldt, D., and W. Edwards, *Decision Analysis and Behavioral Research*, Cambridge University Press, New York, 1986 or Goldstein, W.M., and J. Beattie, *Judgements of Relative importance*, presented at ORSA/TIMS Joint National Meeting, Philadelphia, PA, Oct. 1990.

[12] But see B. Hobbs and P. Meier, *Improved methods for considering environmental externalities in resource acquisition*, IDEA, Inc., Report to Oak Ridge National Laboratory, May 1994.

[13] As noted earlier (Chapter 2), the important point is "pre-defined standard". Where natural cut-off points do not exists (e.g. a plant must be "near" a river for cooling water, or "near" a railway for fuel transportation), exclusionary screening must be used with caution. Indeed, where a multi-criteria screening approach is used, setting the criteria implies certain weights. For further discussion of this important point, see Hobbs and Meier, *op.cit.*

[14] Although the CEA had drafted terms of reference for an environmental assessment, further consideration of the site was suspended by the government before the study was ever carried out.

[15] Namely the 45°C maximum temperature limitation on a thermal discharge. Yet in fact this standard was never envisaged as applying to a large thermal power plant, with its huge volumes of effluent.

[16] It has also been used, for example, in the site selection studies for the Lahkra coal fired power plant in Pakistan (See e.g. *Environmental and Social Soundness Assessment, Lakhra Coal Mine and Power generation* Project Report by Environmental Science and Engineering, Inc. and KBM Engineering and Applied Sciences Inc to the Pakistan Water and Power Authority, march 1987).

[17] see M. Rowe *et al.*, *An Assessment of Nuclear Power Plant Siting Methods*, Report NUREG/CR-1689, U.S. Nuclear Regulatory Commission, Washington, DC, 1979.

[18] In Figure 6.4 we have shown the shape of the trade-off curve to be concave (with respect to the origin). There is no general theoretical requirement for this to be the case. Often what happens is that if one perturbs some base case with a range of options, one at a time, a convex trade-off curve is formed; but when one combines some of the options together, and particularly if one combines individual options that lie of the trade-off curve, then the curve becomes concave (with respect to the origin), as shown in these figures.

[19] This discussion uses the definitions of E. Crousillat and H. Merrill, *The Trade-off/Risk Method: A Strategic Approach to Power Planning*, World Bank, Industry and Energy Department Working Paper: Energy Series Paper 54, Washington, DC, 1992, p. 16-17. This syudy presents two applications of multi-criteria analysis to power systems planning in Poland and Costa Rica. In the Hungary study, SO_2 emissions were used as one of the criteria (together with present value of total cost, present value of new capital required, loss of load probability, and oil consumption), while in the Costa Rica study a composite index representing several indicators was used as the "environmental" attribute.

[20] Given that preferences for attribute levels might be non-linear (as for example in Figure 6.1), it could be argued that m_i and e_i are dependent upon the level of $A_i(P_j)$, rather than being independent of level. For simplicity, we disregard that complication here.

[21] Another way of phrasing this is that looking only at a two-dimensional trade-off curve ignores any joint costs and benefits. For example, one could derive the cost of different options to reduce GHGs in terms of $ per ton of carbon avoided by looking just at the attributes GHG emissions and system costs. But this ignores any additional benefits from joint reductions of SO_2 emissions, and any additional costs of impacts associated with renewable technologies (such as hydro, which certainly reduce GHG emissions, but only at the cost of local impacts associated with inundation). We return to just this point later in Chapter 9 in the presentation of case study results. One might note in passing, however, that most of the estimates of the cost of greenhouse gas emission reductions encountered in the global warming literature do indeed ignore joint benefits and costs -- in other words, they are based just on a two-dimensional view.

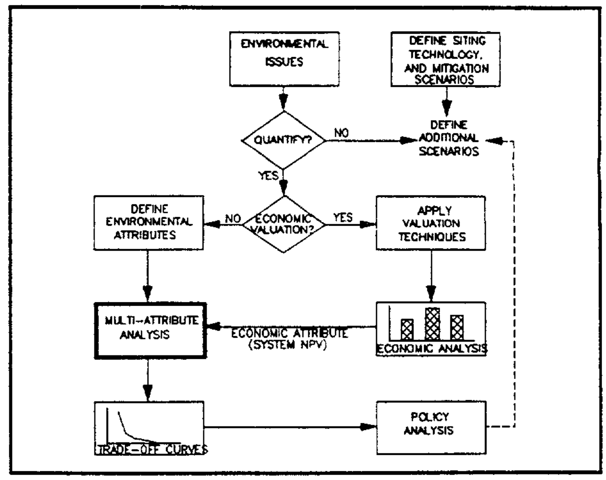
[22] In the more popular lexicon, it is in this quadrant that one encounters "win-win" options (while in Quadrant I one finds "lose-lose" options).

[23] A similar example is given in *Assessment of Multiple Objective Water Resources Projects: Approaches for Developing Countries*, United Nations Environment Programme, United Nations, New York 1988.

[24] It is of course also true that we have used a highly contrived example here to make our point!

[25] This is the approach used in the ENVIROPLAN model: see Annex for a brief overview of this model.

7. APPLICATIONS OF MULTI - ATTRIBUTE ANALYSIS



Multi-attribute methods have been used for some time in power plant siting and transmission line routing studies, and over the past decade have started to be used for this propose in developing countries as well. At the same time, they have begun to be proposed for more general application in energy sector and power sector planning. In this Chapter we review some of these applications, including their use in Sri Lanka itself.

Trade-off curve studies

Over the years a number of studies have been published that have used trade-off curves to illustrate key conclusions. The first example we encountered in the literature is Ferrel (1978), who examined the trade-off between cost and SO_2 emissions.[1] A good recent example is the study by Amagai and Leung (1991), who present an analysis of the trade-off between cost and CO_2 emissions in the Japanese power sector. It might be noted that the study only examined generation expansion and dispatch options, and did not examine mitigation alternatives, demand side management, or tax options. The results are displayed on the trade-off curve depicted on Figure 7.1.

Although the display of trade-off curves can be very useful to decision-makers, there are the

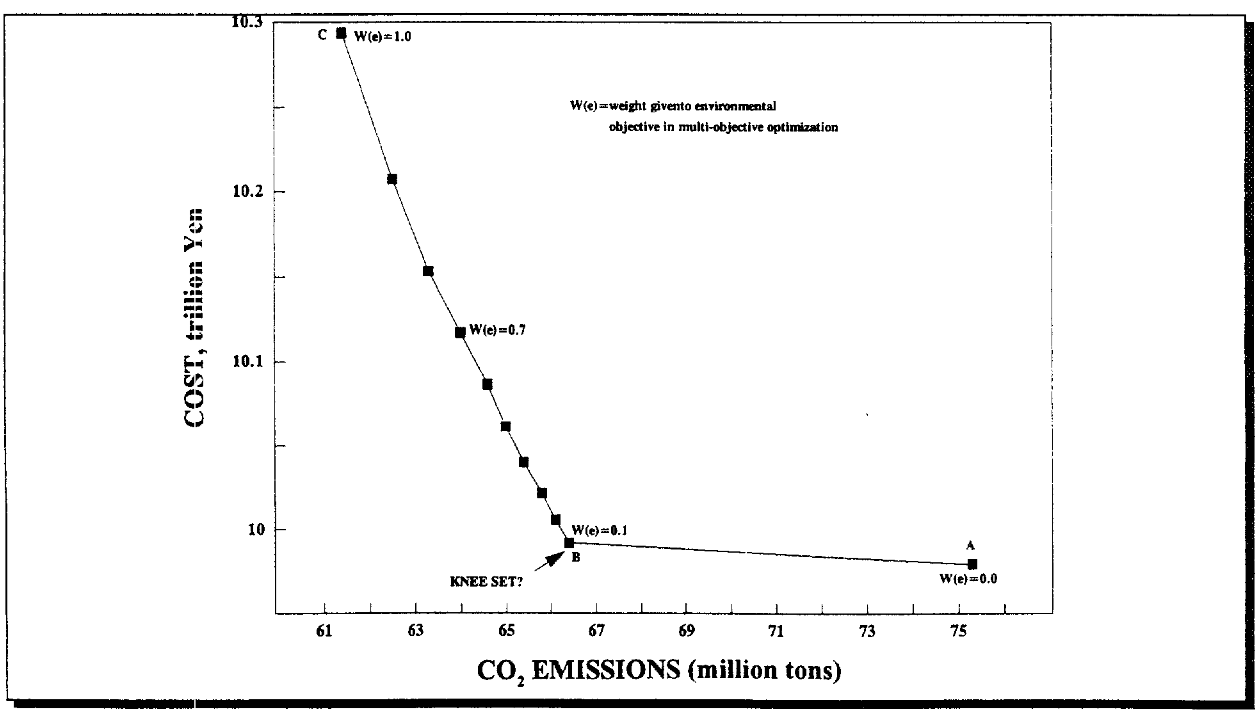


Figure 7.1: Trade-off curve for the Japanese Power sector
(from Amagai and Leung (1991)

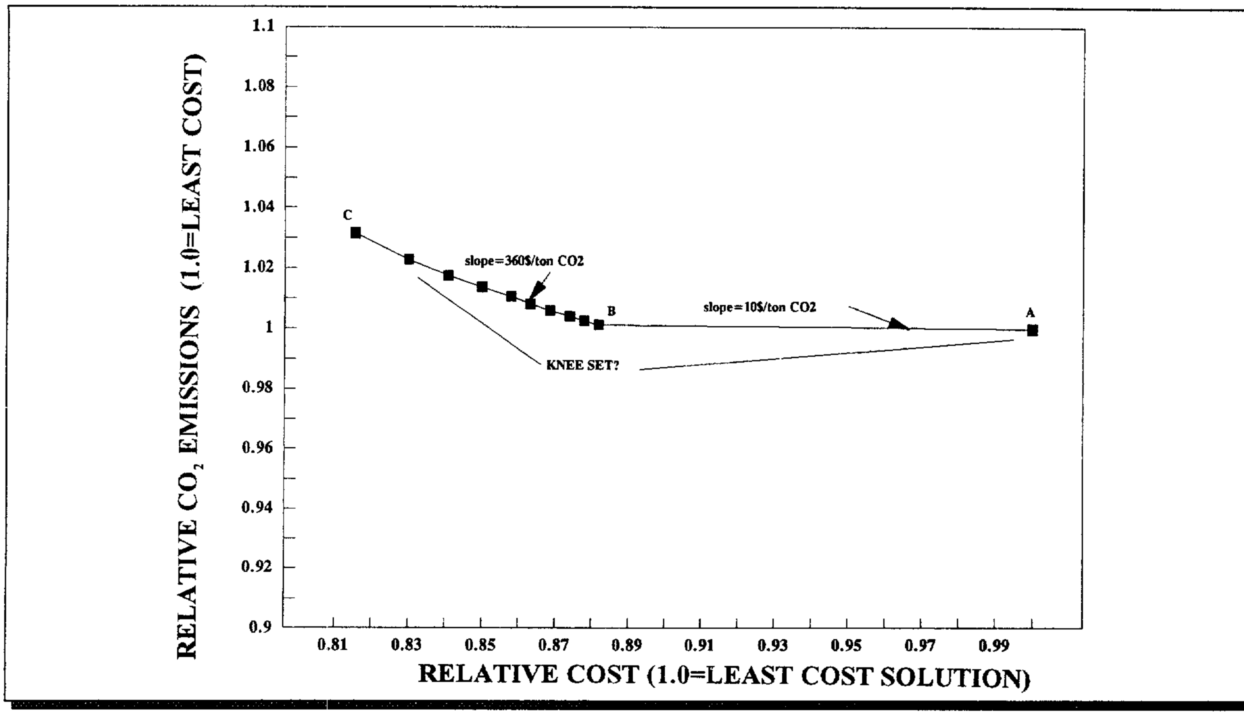


Figure 7.2: trade-off curve for the Japanese power sector on a relative scale.

usual dangers of misinterpretation created by choice of scales. For example, there may be great temptation, on intuitive grounds, to assume that the knee set of Figure 7.1 occurs near point B. However, when one redraws Figure 7.1 on a relative scale (Figure 7.2), such that the least cost solution (at A) is given the value 1.00, the importance of mathematical rather than intuitive definition becomes clear.

As is obvious from this figure, if "significantly worse" in cost means anything greater than , say 3% of the least cost solution, then all of the points on the segment BC are equivalent in cost, but do differ significantly in CO_2 emissions: that is, while the least cost and least CO_2 solutions differ by 3.5% in cost, they differ by almost 20% in CO_2 emissions.

A second caution relates to the interpretation of the slope of the trade-off curve itself. For example, on Figure 7.2, the slope of the trade-off curve changes dramatically from about $10/ton on the right, to 360$/ton on the left. The implication for policy-making would appear obvious: while one can reduce the first 12% of CO_2 emissions for 10$/ton, further reductions incur very sharp cost penalties of 360$/ton.

If CO_2 emissions were the only other attribute of interest, then such an interpretation of the slopes is indeed straight forward. However, if there are n attributes of interest, then the slope of a two-dimensional trade-off curve implies that all other n-2 attributes have been valued at zero. Thus in a three-dimensional case, say in which the third dimension represents population exposure to SO_2, the statement that the slope of the cost-CO_2 emissions curve is x $/ton of CO_2 removed implies that the benefits of any concomitant SO_2 removal (or costs of increased externalities associated with more hydro in the system) are all valued at zero.

Thus, returning to the numerical example of Figure 7.2, since the solutions on the steep part of the curve involve increasing use of hydro and natural gas, CO_2 is not the only pollutant whose emissions are reduced in this portion of the curve. Consequently, the expenditure of the first $360 may not only reduce CO_2 emissions by one ton, but also reduce SO_2 and NO_x emissions. It may also increase the externalities associated with additional hydro plants.

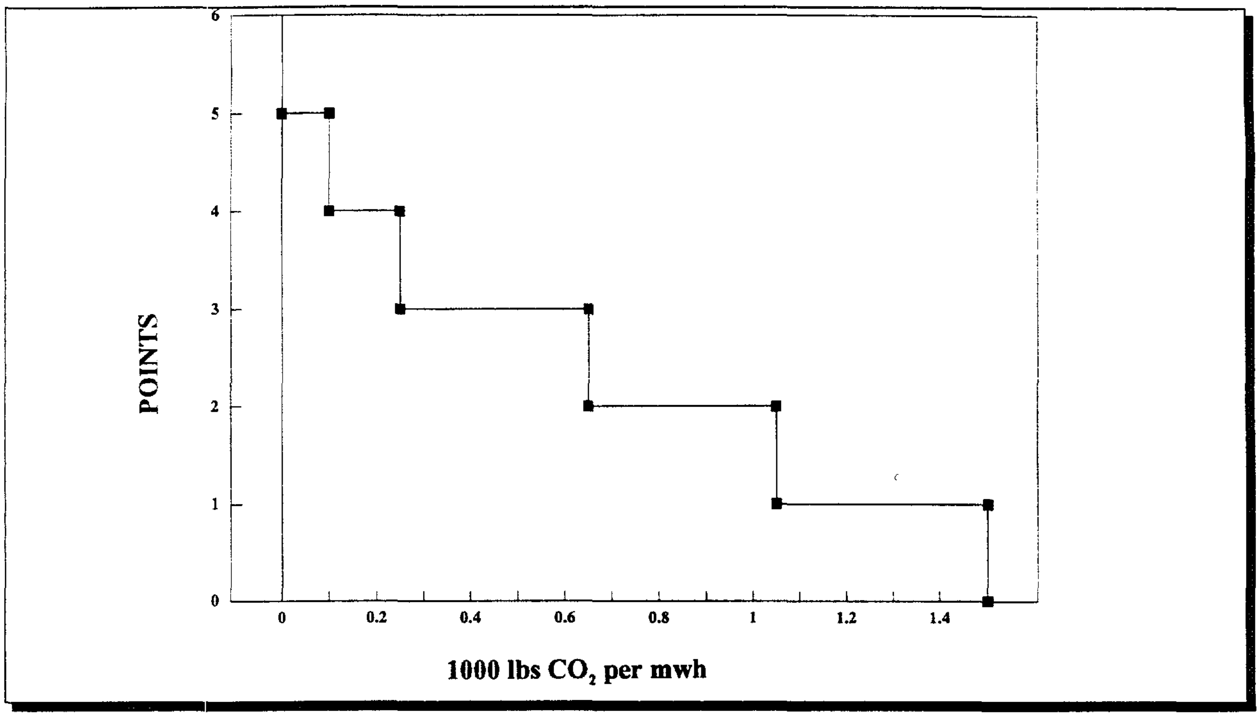


Figure 7.3: The attribute scaling function for CO_2 emissions in the environmental scoring system for Niagara Mohawk (in New York)

Multi-attribute "scoring" systems in planning.

The use of multi-attribute "scoring" systems in planning studies has increased rapidly in the United States over the past few years. These include the use of what are essentially weighting-summation methods in regulatory proceedings, and in bidding systems used by some utilities to acquire capacity from independent power producers.[2] Mintzer[3] provides a typical rationale: "...scaled scoring systems are easy to use,[4] facilitate comparisons of environmental impacts measured in different units, and are more comprehensive than economic analysis ... using weighted scaled scores, technologies (or a combination of technologies contained in an energy futures scenario) can be ranked from the least to the highest cost on the basis of all economic, environmental and social costs that can be quantified." These are very impressive claims, but, unfortunately, many of the applications have paid little attention to methodological issues,[5] with the consequence that the validity of the results is highly uncertain.

A general problem is inconsistency. In some bidding programs approved by the New York Public Utility Commission, the bid prices are adjusted to reflect externalities -- for example SO_2 emissions are valued at $832/ton, and CO_2 at $1.1/ton, valuations that are based on control costs. In others, the bidding programs require the use of so-called "environmental scoring forms", essentially weighting summation .

Table 7.1 presents such an example as used by the Niagara Mohawk utility in New York: there the "weight" assigned to SO_2 is 7, and to carbon dioxide 3.[6] The claim is made that the scoring forms are supposed to reflect "the environmental perceptions in each utility service area" (Putta, 1990); yet it seems fairly clear that "weights" can be manipulated in such a way as to produce almost any desired result.

The problem of validity in scaling is illustrated in Figure 7.3: the scaling function is arbitrary, it is unlikely to have interval properties, and there is a lack of normalization.[7] It is in fact quite common to encounter systems in which the physical attribute is converted into a step function corresponding to some number of points on a scale. However, in the absence of

Table 7.1: The environmental scoring system for Niagara Mohawk.

Environmental Attributes	Weight (W)	Points (P) 0	1	2	3	4	5	Score (W x P)
Air Emissions								
Sulfur oxides (lbs/MWh)	7	>6	4.0-6.0	2.5-3.9	1.5-2.4	0.5-1.4	<0.5	
Nitrogen oxides (lbs/MWh)	16	>6	4.0-6.0	2.5-3.9	1.5-2.4	0.1-1.4	<0.1	
Carbon dioxide (lbs/MWh)	3	>1500	1050-1500	650-1049	250-649	100-249	<100	
Particulates (lbs/MWh)	1	>0.3	0.2-0.3	0.1-0.199	0.05-0.099	0.01-0.049	<0.01	
Water Effects								+
Cooling water flow (Annual intake as % of lake volume)	1	80-100	60-79	40-59	20-39	5-19	<5	
Fish protection	1	None		Operational restrictions		Fish protection provided	No public water used	
NYS water quality classification of receiving water	1	A or better	B	C+	C	D	No water use or municipal water/ wastewater utilized	
Land Effects								+
Acreage required (acres/MW)	1	0.3-0.5	0.2-0.29	0.1-0.19	0.05-0.09	0.01-0.05	<0.01	
Terrestrial	1	Unique ecological or historical value		Rural or low density suburban		Industrial area	No land used	
Visual aesthetics	1	Highly visible		Within existing developed area		Not visible from public roads		
Transmission	2	New OH >5 miles	New OH 1-5 miles	New UG >5 miles	New UG 1-5 miles	Use existing facilities	Energy conservation	
Noise (L_{eq} - background L_{90})	2	5-10			0-4.9		<0	
Solid waste disposal (lbs/MWh)	2	>300	200-300	100-199	50-99	10-49	<10	
Solid waste as fuel (% of total Btu's)	1	0	1-30	31-50	51-80	81-90	91-100	
Fuel delivery	1	New RR spur	Truck & existing RR	New pipeline	Barge	Use existing pipeline	No fuel use	
Kilometers from sensitive receptor area (per 6 NYCRR 225.1.1 (b)(4))	1	<10	10-39	40-69	70-100	>100	Energy conservation	
							Total Score (210 Max.)	=

Source: Putta (1990),p.47

some specific threshold effects that would justify some deviation from the presumption of linearity, much better would simply be to maintain the original physical attribute values, and simply normalize to a 0-1 scale. Risk aversion could also lead to non-linearity in such transformations. The important point here is (1) that transformations ought not to be arbitrary, and (2) that scale transformations do not substitute for proper normalization.

Problems of attribute definition abound. For example, what exactly is the environmental consequence that is expressed by "land use" in acres (or acres/Mw). Differences in market value of the land should be reflected in the capital cost of a technology, and the opportunity costs of lost production (say in the case of agricultural land) are also readily quantified in economic terms. Therefore, it is only the non-market values of land that need to be captured. If there are unique historical, ecological or archaeological characteristics then they are surely not captured by a value for acres per Mw; in any event most scoring systems already have an attribute for this concern. In short, there is little evidence that the environmental attributes in some bidding systems have been thought through in a logical fashion.

There has also been much controversy over double-counting. For instance, in the case of SO_2 emissions, the national cap imposed by the Clean Air Act Amendments of 1990 ensures that an increase in emissions in one place will be offset by a decrease elsewhere, resulting in no net change in emissions. Thus, it has been argued that the only penalty that should be assessed against SO_2 emissions is the market cost of allowances;[8] consequently, the Massachusetts Public Utility Commission assessment of an additional penalty upon SO_2 is double counting. However, this may not be double counting if Massachusetts judges that SO_2 emissions have worse effects within the State than elsewhere; but such a judgment would require consideration of where (and under banking schemes, when) such emissions would occur if not within the State at the present time.[9]

All of these problems have in fact begun to be recognized in the literature. For example, Hirst and Goldman (1991), discussing the scoring system used by the New England Electric System, conclude "..the method is easy to understand, but its lack of scientific basis is troubling".

Analyzing energy-environmental trade-offs in Asian countries

A recent ADB study on environmental considerations in energy development proposed the use of a multi-attribute methodology to assess trade-offs between energy policy and environmental objectives.[10] The approach is documented in the main report by example (albeit to some hypothetical country for which given environmental regulations were hypothesized). Since attempts are currently underway to apply this method in a number of country studies in Asia,[11] and is relevant to our own study, the proposed methodology bears examination.

Although not expressly stated as such, the methodology uses the basic weighting summation approach; six attributes were chosen, scored, weighted, and two strategies evaluated upon the aggregate scores. Unfortunately it appears that the interests of simplicity (".. one should not detract from the understanding of how the techniques are used in principle") weakened the validity of the results. Application of the methodology would be more credible if key methodological requirements had been more rigorously analyzed, and the question of attribute scales been examined in more detail.

Indeed, actual application of the approach to the subsequent country studies, proved quite difficult. In the case of India, the approach was not applied at all because it was recognized that applying scores to emission levels was a poor indicator of actual environmental impact. In the Indonesian study, multi-attribute analysis was used, but only to the point of estimating and displaying trade-off curves, without any attempt at using the weighting summation method as a decision rule. Only in the China country study was the methodology applied as originally proposed in the ADB publication, but even here certain problems were encountered.

Some of the practical difficulties are illustrated by the air quality attribute. In the

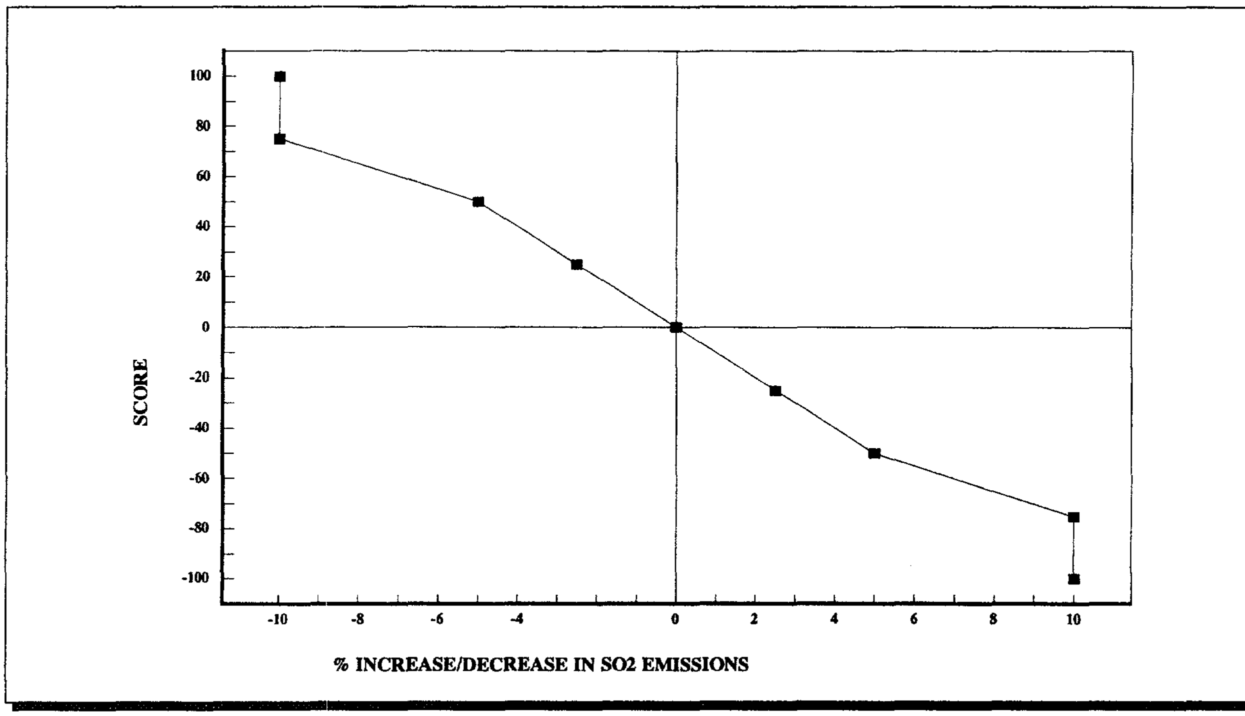


Figure 7.4: The scale for air quality

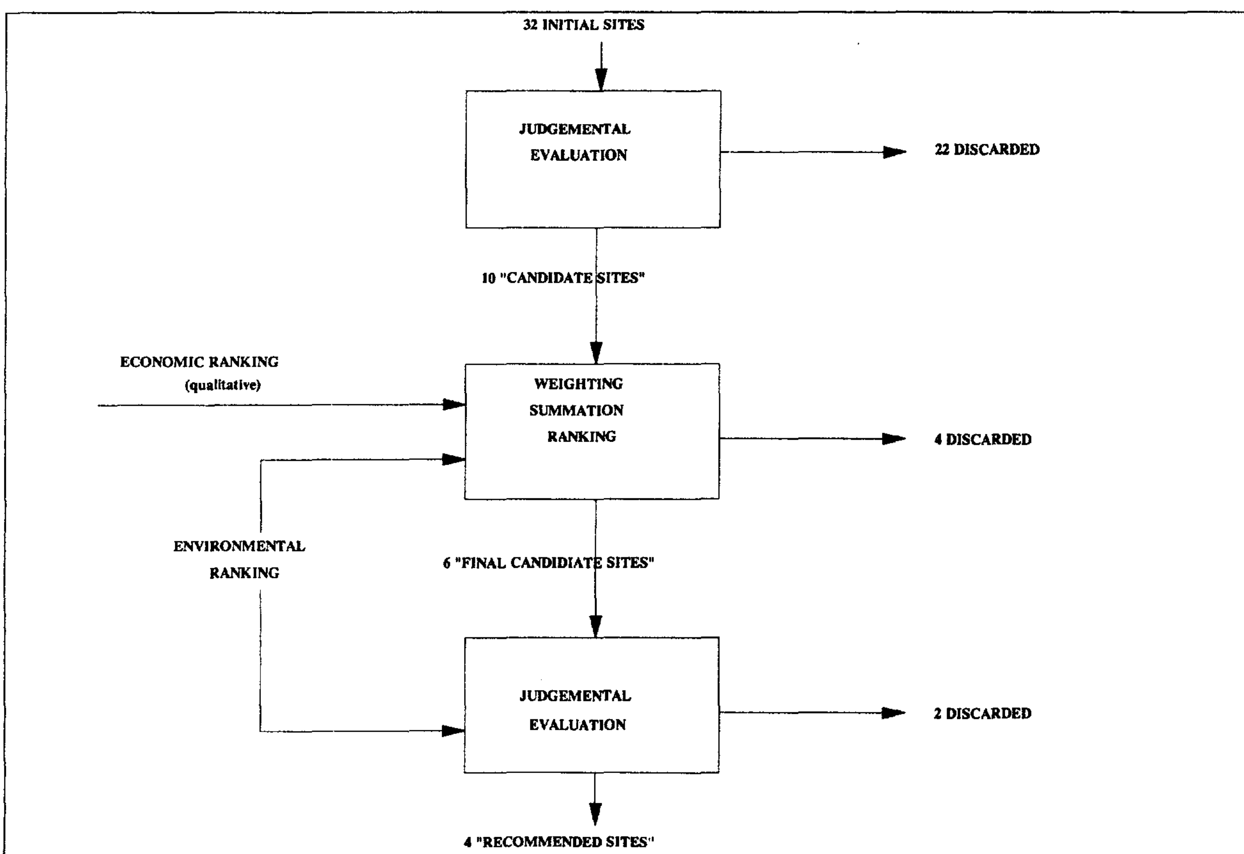


Figure 7.5: The site screening process in the BVI Thermal Options Study.

example used, the postulate was that in the country in question, the ambient air quality levels currently met WHO guidelines, but that a 10% increase in emissions would result in a violation of the standard. The following scoring system was proposed:

Score	change in emissions
+100	>10% decrease
+75	10% decrease
+50	5% decrease
+25	2.5% decrease
0	current situation
-25	2.5% increase
-50	5% increase
-75	10% increase
-100	>10% increase

This scale is illustrated on Figure 7.4. However, if in fact the objective was to eliminate any strategy that might violate the standard, then a better decision rule would be exclusionary screening. Most importantly, however, is the need to be specific about exactly whose values are reflected in the scaling system proposed: otherwise it is surely preferable to compare alternatives on the basis of an unambiguous scale. Emissions may or may not be related to impacts, but they are unambiguously quantifiable.

The consensus of the researchers involved in the ADB study, as expressed at the recent symposium on Environmental Considerations in Energy Planning,[12] was that while multi-attribute methods did have great promise as a way of dealing with the quantification of externalities that could not easily be valued, application of decision rules (such as weighting summation) needed to be viewed with great caution.

Multi-attribute siting studies in Sri Lanka

The weighting summation method was used by BVI in both the initial Trincomalee site selection as well as in the subsequent Thermal Options Study.[13] In general, site-selection is a four-step process:

1. The selection of candidate areas.
2. The definition of a set of candidate sites in these candidate areas.
3. The analysis of the candidate sites to a short list for final site selection.
4. The selection of the final site.

It is in steps (3) and (4) that the weighting summation method is most often used. This process is illustrated for the case of the thermal options study on Figure 7.5.

A number of the general issues identified in the previous chapter about attribute selection and scaling are well illustrated by this application. At the outset one might note that the BVI thermal options study was the first attempt at systematically comparing alternative locations for large fossil-fueled baseload plants that might have a potentially significant impact on air quality. However, most of the discussion of air quality concerns is qualitative: for example, the discussion of the Matara site is as follows:

> *Site M-1, Kudawella East:*
> The ambient air quality in the Matara siting area is good. The residential population within a 1.6Km radius of the boundary of the site is estimated to be 260 and 270 households. Additional sensitive air quality receptors indicated on the survey department sheet for Negombo within the 1.6Km radius are two schools.[14]

Based on these kinds of somewhat ambiguous assessments, sites were then assigned a score for "air quality", as illustrated on Table 7.2. On the 30-point scale used for air quality, 30 is the best, 0 is the worst. The basis for the scoring is described only in very general terms as "number of sensitive receptors and the exposure risk of significant receptors". Even as relative indications these scores are very ambiguous.[15] Finally, it is unclear whether the scores are comparable across the various generation types.[16] One can only speculate, therefore, why a coal plant at Sapugaskanda would have an air quality score of 11, while a diesel plant is scored at 13. In the Annex we go on to examine some of the problems associated with applying the weighting summation procedure as a decision rule.

Table 7.2: Air Quality Scores in the BVI thermal options study

site ID	site	cc[a]	oil	coal	diesel
NC-1	Mundal East	21	20	20	20
NC-3	Bolawata	21	20	20	20
NC-5	Ekala	21	20	20	20
C-1	Mahawetta				7
C-3	Kelanitissa	6			5
C-6	Peliyagoda	11	6	6	11
C-7	Sugathasua	6			5
C-8	Yakbedda	11			11
C-10	Sapugaskanda	13	11	11	13
C-11	Siyambalape	13	11	11	13
C-12	Biyagama	13	11	11	13
G-3	Bope				13
G-6	Armitage Hill				13
G-7	Haliwate				13
G-8	Wakawella	13	9	10	13
G-9	Bataduwa	13	9		13
M-1	Kudawella East	30	28	29	27
M-16	Weligama	30	28	29	27

[a] CC=oil-fired combined cycle

Conclusions

There are several lessons to be drawn from these examples that are of relevance to the design of our own study:

1. Inadequate recognition is given to the existence of theoretical requirements for a valid use of the weighting summation method. The lack of proper normalization, and violations of the use of measurement theory in algebraic manipulations of ranks, make the results questionable. These requirements do affect the results, and need to be carefully considered.

2. Rarely are attempts made to display trade-offs graphically. The reader of the BVI Thermal Options study, for example, would have to review 46 dense tables of scores and ranks in order to follow the analysis. Moreover, had the attribute scales used in the ADB study been displayed graphically, some of the weaknesses might have been recognized.

3. In some cases in the BVI studies it is not stated whether the individual attributes (air quality, water quality, etc) were individually scored (did the air quality expert only rank air quality, and a water quality expert rank only water quality), or whether the individual attribute scores already reflect a consensus among specialists. Nor was it clear how the relative weights were determined, or whose values they represent.

4. There is no point in transforming physical measures of attributes into "scores" unless the latter can be logically justified on the basis of actual, or even hypothesized environmental damages. The use of arbitrary transformations makes the results unreliable, and subject to the criticism that they results have been manipulated.

5. Neither the BVI or ADB studies attempted to identify alternatives that reflect the critical trade-offs (knee sets, non-inferior sets etc.).

Annex

Siting Studies in Sri Lanka

There are a variety of methodological concerns that are well illustrated by the siting studies done in Sri Lanka in the mid 1980s. These concerns are offered in the spirit of constructive comment to further a better understanding of the issues, and to draw the necessary lessons for our own case study.

The first concerns some basic methodological procedures. Table 7.3 summarizes the procedure used for final site selection in the Trincomalee study: the most favorable site was assigned rank number 7, the least favorable rank number 1.[17] The ranks were determined by "..specialists knowledgeable about each of these siting factors", and consensus weights were estimated by "several siting specialists". The final scores were calculated as follows:

> "...The rank numbers were *multiplied by the factor weights* for each factor and the products summed to produce a weighted rank total for each site." (Our emphasis).

Unfortunately, this procedure is inconsistent with one of the fundamental axioms of measurement theory: i.e. one may not, in general, perform arithmetic operations on ordinal numbers (ranks). The results are therefore not reliable. Nevertheless, the point is not that we necessarily disagree with the conclusion-- rather it is that the conclusion is not based on a scientifically rigorous procedure. Neither is the justification well founded:

> "...Weighted ranking systems are commonly used in Engineering circles in the United States to evaluate factors other than costs: these ranking methods are particularly applicable to siting studies, since at least one of the major siting factors cannot be evaluated with costs. Black and Veatch International has prepared many siting studies involving different geographical states in the United States which involved use of this method."[18]

This application illustrates another problem in the application of such methods. Five of the six attributes used here are in fact based on costs:

Table 7.3: Site Rankings in the Trincomalee Study

site	coal unloading	transmission	site	generation facilities	supporting infrastructure	land use environment	overall ranking
"consensus" weights >	25%	10%	15%	20%	10%	20%	
1	2	1	2	1	4	7	2.7
2a-1	7	3	3	5	6	4.5	5
2a-2	6	3	4	7	6	6	5.6
2a-3	5	3	6	6	6	4.5	5.2
3a-1	4	5.5	5	3	2.5	2	3.8
3a-2	3	5.5	7	4	2.5	2	3.6
4	1	7	1	2	1	2	2

Source: Black and Veatch, *Trincomalee Thermal Power Project, Site Evaluation and Selection Study* Phase II Final Report, September 1985, p.10-1.

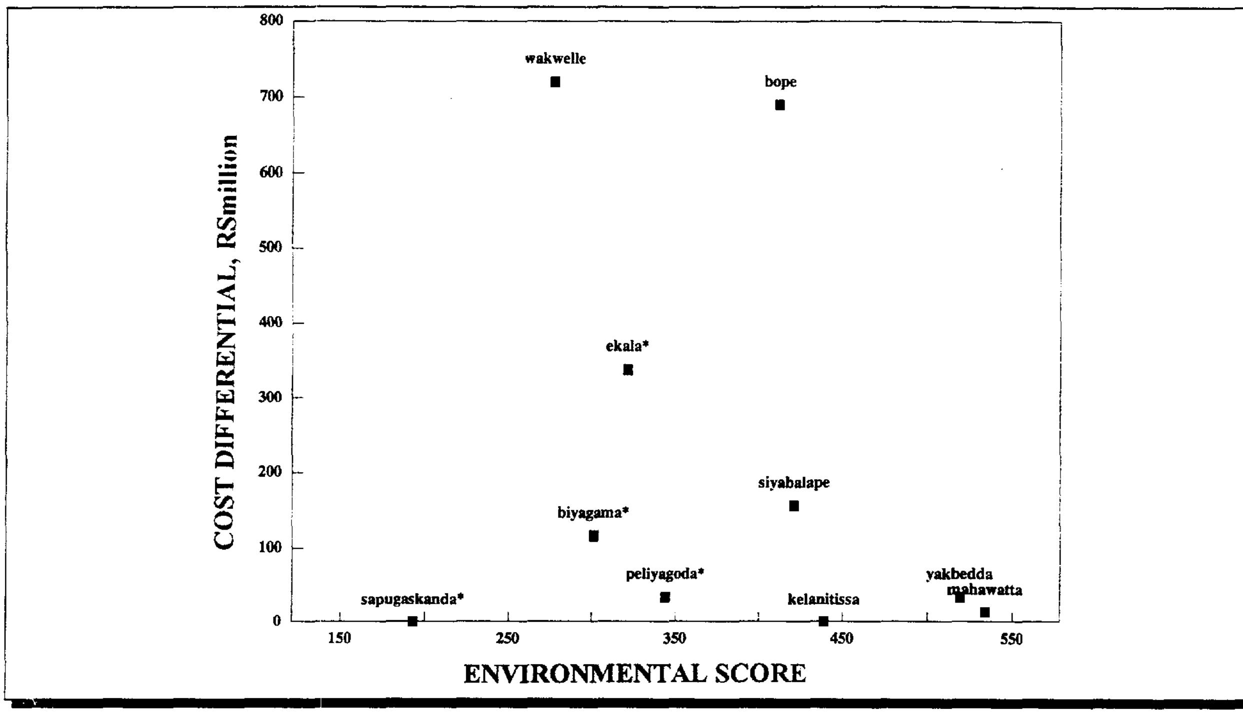


Figure 7.6: The final recommendations for diesel plants in the Thermal Options study

indeed, we are told "..capital costs and expected costs of operation were generally used as a basis for ranking the sites". If in fact the purpose of the exercise is to examine the trade-off between "land use and environmental factors on the one hand", and factors related to system costs on the other, then everything related to cost should be subsumed into a single cost attribute.

The Thermal options study shares many of the same weaknesses. For example, it is stated that "..an important consideration in comparing the scores shown on Tables 4.3-2 and 4.3-3 is that the scores provide the basis for a site ordering, but relative score values are less important. That is, a site with a score of 800 is not necessarily twice as good as a site with a score of 400"[19] Yet if the attribute scores primarily indicate "ordering", they should certainly not be weighted and added.

At least in the final site selection process in the thermal options study, these pitfalls were avoided in that the final recommendations were based purely on judgmental evaluation, and properly described as such. In fact, had the trade-offs been displayed graphically, as shown on Figure 7.6 in the case of the diesel plant selection, the sites finally recommended (indicated with an *), all lie in the expected lower left hand quadrant (which contains the sites with both low environmental scores and low economic costs). Again, however, the underlying assumptions used for the calculation of the environmental scores remain unclear.

Notes

[1] Other early examples include P. Meier and L. Ruff, The spatial dimension of regulatory cost assessment, Report to the National Commission on Air Quality, Washington, DC, 1979; and H. M. Merrill, F. C Schweppe and D. C. White, Energy strategy planning for electric utilities: the SMARTE methodology, IEEE Transactions on Power Apparatus and Systems, PAS-101, 2, pp. 340-346, Feb. 1982.

[2] For a rigorous mathematical analysis of the weighting summation technique, see e.g. P. N. Smith, Testing the sensitivity of linear additive weighting to variations in a criterion weight, Project Appraisal, 7, 2, pp. 107-109, June 1992.

[3] I. Mintzer, *et al. Environmental externality data for energy technologies*, Center for Global Change, University of Maryland, July 1990.

[4] Indeed, it could be argued that such schemes are merely economic valuations in disguise (as noted by S. Weil, The new environmental accounting: A status report, Electricity Journal, 4, 9, pp.46-54); thus, because scoring systems are "easy to use" it must be because the users are disregarding the enormously difficult issues of environmental trade-offs.

[5] It might be noted that the proposition that utility regulatory commissions should get into the business of what in effect amounts to environmental regulation beyond that of the environmental agencies themselves is far from universally accepted -- see e.g. A. E. Kahn, An economically rational approach to least-cost planning, Electricity Journal, June: 11-19, 1991; or L. Ruff, *Internalizing environmental costs in electric utility decisions*, Putnam, Hayes and Bartlett, Washington DC, 1991. The basic objection is that if environmental standards are already at the optimum point as required by economic theory (i.e. at the point at which marginal cost of abatement equals the margin benefit), then any additional abatement or costing of the residual emissions would be non-optimal. And if, alternatively, and as is more likely, the standards are *not* at the optimal point, there is little likelihood that the additional abatement cost (or foregone benefits by moving to another supply resource) will bring one any closer to the optimum than is already the case in the absence of that additional regulation. However, even to the extent that regulatory commissions recognize that second-best solutions are being advocated, they seem determined to forge ahead anyway. (See e.g. note 27 of Chapter 5, *supra*).

[6] Although at first glance the relative weights (SO_2 to CO_2) of 7 to 3 appear inconsistent with the NYPUC valuations, when one takes into consideration the scales used, the ratios are comparable. a reduction of 7lb of SO_2 are seen to be worth 7 x 5 = 35 points, while a reduction of 1,500lb CO_2 is seen to be worth 3 x 5 =15 points. Thus 1 lb SO_2 is seen to be equivalent to 650lb CO_2 (which follows from the value w that satisfies the ratio 7/35= w 1750/15) , which is not totally inconsistent with the $1.1 to $832/ton valuations. The important point here is that the lb to lb trade-offs are not at all obvious when choosing weights!

[7] Step functions of the type shown on Figure 7.3 are generally to be avoided. For a detailed review of US bidding systems, see e.g. C. A. Goldman, J. F. Busch, E. P. Kahn, S. S. Stoft and S. Cohen, *Review of integrated resource bidding at Niagara Mohawk*, Report LBL-31667, Lawrence Berkeley Laboratory, Berkeley, CA, May 1992; or M. Kliman, Competitive bidding for independent power: developments in the USA, Energy Policy, pp.41-55, Jan. 1994.

[8] Hutchinson, M. A., *Emission caps, externalities and double counting: why certain externalities should not be included in new resource planning*, in DSM and the Global Environment, Synergic Resources Corporation, Arlington, VA, 1991.

[9] See e.g. B. Hobbs, Environmental adders and emissions trading: Do they mix?, Electricity Journal, 5, 7, pp.26-34, 1992.

[10] Asian Development Bank, *Environmental considerations in energy development*, Manila, May 1991.

[11] In Indonesia, India and China. The Indonesia study is available as *Environmental consideration in energy development project: Indonesia country study*, Report to the Asian Development Bank by the Institute of Technology Bandung, Report PPE/KLN/91-03, Bandung, Indonesia, Nov. 1992. The India country study is available as *Environmental considerations in energy development: India country study*, Report to ADB

by the Tata Energy Research Institute, New Delhi, December 1991.

[12] Held at ADB in Manila, February 1992

[13] As noted earlier, the method is in fact in quite widespread use in developing countries. For an example in Indonesia, see e.g. *Feasibility study for East Kalimanthan coal/gas fired steam power plant: Volume V; Main report, environmental Impact Analysis*, Report to PLN by Econona Engineering and Black & Veatch International, 1989. The analysis looked at four different sites and 14 environmental criteria (see p.II-7 for the scoring table).

[14] BVI Thermal Options Study, Volume II, page I-29. Negombo is nowhere near the site in question: this is presumably an editorial error. But more importantly, nowhere is there given an explanation as to why the relevant radius is 1.6 km(=1 mile).

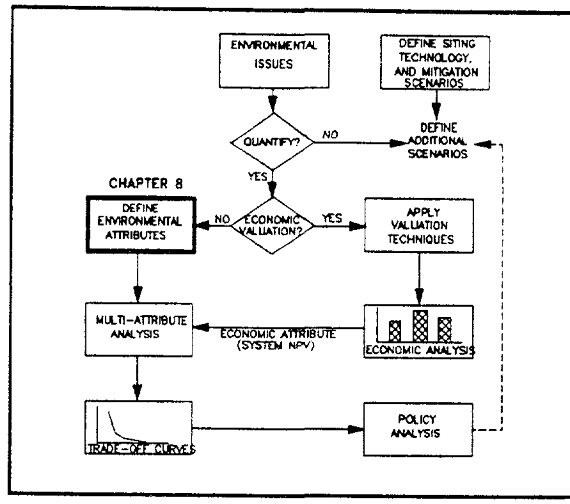
[15] Nevertheless, these scores were then combined with other scores, derived on a similarly weak foundations, in a multi-attribute ranking of sites. We defer discussion of this overall ranking procedure to the Annex.

[16] In the main report notes that "..Appendix C ..provides some discussion as to the basis for the scoring process" (Main Report, p.4-22). Unfortunately, Appendix C contains no discussion of any kind, just the scoring tables.

[17] Black and Veatch, *Trincomalee thermal power project, site evaluation and selection study phase II final report*, September 1985. The site selection procedure is described in Section 10 of that Report.

[18] BVI, *op. cit.*, p.10-1

[19] BVI Thermal Options Study, Volume I, p.4-25.



8. ATTRIBUTE DEFINITION

We now turn to the definition of the environmental criteria to be used in the multi-attribute analysis. Environmental attributes are required for those impacts that have been identified as being important to national policy (as per the discussion of Chapter 3), which can be quantified, but which cannot be valued economically (or where the valuation process is subject to high uncertainty and controversy). We also need to define the appropriate criterion for the economic attribute.

Selection criteria

Perhaps the most important criterion in deciding which environmental issues to address is to be clear about the scale of analysis that is required at the system planning level. Many impacts that are purely local in nature can safely be deferred to the project level EIS stage without running any significant risk that these would ultimately stand in the way of implementing a strategy identified at the planning stage. Thus, in the case of Trincomalee, while it may well be true that a number of very vocal interest groups raised objections based on very narrow issues (whale watching, oyster beds), the issue that in fact prevailed was the view held by the broader environmental community that discharge of effluents into shallow waters constituted a broad risk to aquatic ecosystems. The trade-off to be examined in system planning studies, therefore, concerns the cost of various cooling system options to limit thermal discharges, not the presence or absence of specific species at specific locations. The latter is, however, the proper concern of the project level EIS.

Obviously judgements must still be made; and there may be some impacts that at some projects are purely local, at others of national significance. Resettlement at hydro plants is a good example: at some projects, the resettlement impacts may be quite small, and would neither strain the ability of local authorities to manage, nor would they be likely to become a political issue at a national scale. But at other sites, the scale of resettlement needs may be such that indeed it may require the attention of national decision-makers. Certainly if the high dam variant of the Kukule project is built, the need to resettle some 11,000 people defines an issue of national importance; on the other hand, the run-of-river variant would displace only 135 people in 27 families. In any event, as already noted, the costs of resettlement can be substantial, and must therefore be regarded as potentially significant even in purely direct economic terms.

The guidelines set forth in Chapter 6 clearly have broad validity. There is no great advantage in trying to include a very large number of narrowly defined environmental impacts: not only will this be difficult at the system planning stage where sites that may be needed 20 years hence may or may not have been identified, but more importantly a proliferation of attributes simply clutters the analysis, and makes much more difficult the demonstration of what the really important trade-offs in fact are.

Another issue at this stage is how to draw the boundaries of analysis. In this case study we have bounded the problem in such a way that we have examined only that set of environmental issues that are likely to be of direct importance to national decision-makers. Thus we have not included the environmental impacts associated with the extraction of imported coal (that would arise in Australia or South Africa), except in the sensitivity analysis to coal prices: if in fact Australian policy-makers do decide to include the cost of environmental externalities associated with extraction (say by imposition of rigid land reclamation requirements on the coal mining companies), then that would simply be reflected in a higher coal price to Sri Lanka.

On the other hand we have included the question of greenhouse gas emissions; this is because Sri Lanka decision-makers will need to deal with the issue as part of the international discussions that are now underway, and any international agreements that are reached will surely have repercussions in Sri Lanka itself. The attributes considered in this study are listed in Table 8.1.

Greenhouse gas emissions

The relationship between global CO_2 concentration and the actual physical impacts that may follow, such as sea level rise or changes in monsoonal rainfall patterns, is still poorly understood, and in any event is very unlikely to be captured by simple linear correlations. However, since Sri Lanka's contribution to worldwide emissions will remain extremely small, the assumption of linearity is not unreasonable. In any event, since the focus of current international efforts is primarily on reductions in CO_2, in the first instance Sri Lanka decision-makers will still require information on emissions (especially in light of the possibilities of CO_2 taxes or tradable emission rights that have been advocated by some).

CO_2 emissions are readily calculated based on the carbon content of the fuels concerned by the formula

$$CO_2 = C\,y\,m \qquad (8.1)$$

where C is the carbon content of the fuel (60% for a typical fueloil), y is the oxygenation rate (say 98%), and m is the conversion of CO_2 from carbon, namely m=3.667 (which follows from the corresponding atomic weights). For a 150Mw coal fired plant operated at a 60% plant factor, a heat rate of 8,163 Btu/kwh and a heat content of coal of 11,340 Btu/lb (the design values assumed by BVI for Trincomalee), the total fuel consumption is 283,761 tons of coal per year, and application of (8.1) yields 708,153 tons of CO_2 per year for a 150Mw plant.

It might be noted that SO_2 removal, whether by limestone or lime FGD systems, or by fluidized bed combustion where calcination occurs in-situ, involves the production of CO_2, as indicated by the summary reactions[1]

Table 8.1: Summary of environmental attributes

attribute	units	impact
emissions of carbon dioxide	[1000 tons]	global warming.
population exposure to air pollutants	person-ug/m^3/yr	human health impacts
biodiversity index	[ ]	diminution of biodiversity; impact on habitat of endemic species.
soil permeability	1/[cm]	risk to groundwater resources from coal pile runoff, ash and sludge disposal areas
increase in surface temperature > 1^{o}C	[ha]	ecosystem impacts from thermal plumes.
employment		discounted incremental employment
emissions of acid rain precursors	[1000t/y]	potential for acid rain damages

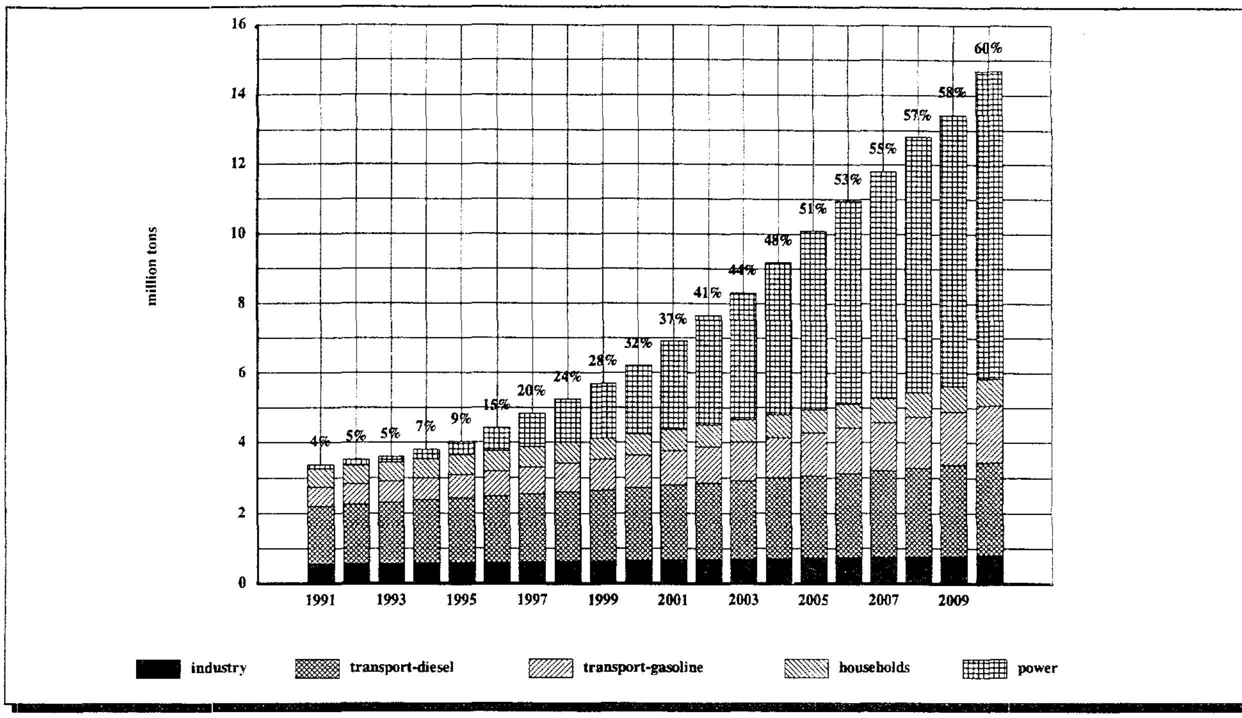


Figure 8.1: CO_2 emissions by sector

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (8.2)$$

$$CaO + SO_2 + 0.5\,O_2 \rightarrow CaSO_4 \qquad (8.3)$$

This implies that for every mole of SO_2 there is produced one mole of CO_2. When one examines the quantities involved, however, in the case of a 1% sulfur coal the contribution of CO_2 attributable from sulfur removal will be less than 1.5% of what is produced by the combustion effect itself, and therefore the effect is ignored. Certainly much more important is the lower overall efficiency at plants fitted with FGD (which is typically 5% lower).

Biodiversity

Detailed biodiversity information at potential power plant sites is unlikely to be available at the system planning stage. Consequently the only quantification that appears possible is to derive a probabilistic index that gives the decision-maker information about the likelihood that the detailed EIS will reveal the presence of an endemic species[2]; significantly impact ecosystems of high biological diversity; or affect a habitat already in

Table 8.2: Relative biodiversity value.

rank	ecosystem	w
1	lowland wet evergreen forest	0.98
2	lowland moist evergreen forest	0.98
3	lower montane forest	0.90
4	upper montane forest	0.90
5	riverine forest	0.75
6	dry mixed evergreen forest	0.5
7	villus	0.4
8	mangroves	0.4
9	thorn forest	0.3
10	grasslands	0.3
11	rubber lands	0.2
12	home gardens	0.2
13	salt marshes	0.1
14	sand dunes	0.1
15	coconut	0.01
16	forest plantations	0.01
17	tea plantations	0.001
18	rice paddies	0.001

Source: This scale was developed by Professor K. D. Arudpragasam, Professor of Zoology at the University of Colombo and former Chairman of the Central Environment Authority.

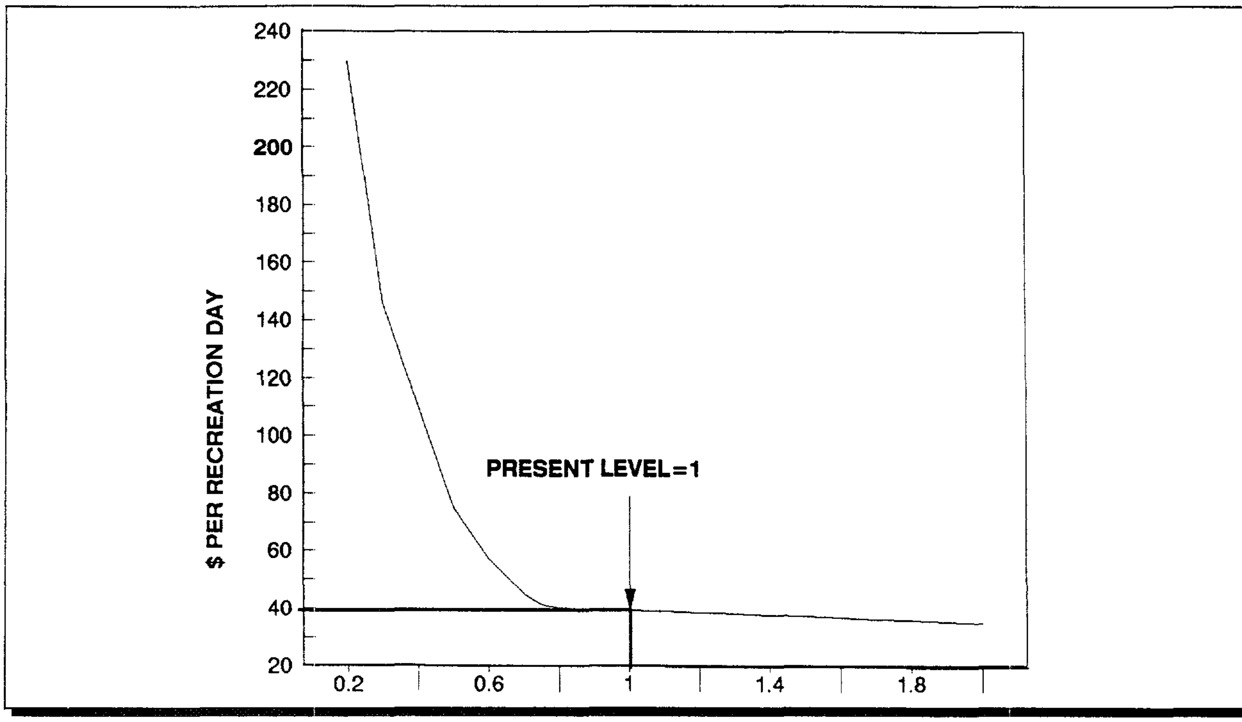


Figure 8.2: Generic value function for habitat loss

a marginal condition. It should again be noted that endemicity and biodiversity are not necessarily correlated: an endemic species may be encountered in an area of low biodiversity, and areas of high biodiversity may contain no endemic species. It is certainly true, however, that extinction of an endemic species would very likely constitute a "show-stopper" at the project stage; and it is also true that at least as far as Sri Lanka is concerned, its endemic species are most likely to be encountered in areas of high biodiversity.

Such an index will have several constituent elements. First is the nature of the impacted ecosystem itself. On Table 8.2 are ranked the main ecosystem types encountered in Sri Lanka, and assigned to them a value, w_j, that captures the relative biodiversity value of different habitats. The scale is to be interpreted as a strict ratio scale, (i.e. zero indicates zero amount of the characteristic involved).

The second element concerns the relative valuation, because the value of the area lost is a function of the proportion of the habitat that is lost. This idea is illustrated on Figure 8.2, which shows the estimated non-market value for resident fish, expressed as $ per recreation day, as a function of the ratio of actual abundance to present abundance. The figure is taken from a study of the environmental costs and benefits in the US Pacific Northwest[3]. The implication is that as the habitat, or the relative abundance, decreases, the value of the remaining resource increases. The implication is that as the habitat declines in size to zero, the value assigned to it tends to infinity (or some extremely high value).

For instance, in the case of Sri Lanka, the point is that the last hectare of tropical rain forest would have infinite value, and hence be unacceptable; whereas, say, if one loses 1 ha out of a remaining 10,000ha, the value given to that ha might be quite modest.

Such an approach to valuation of biodiversity is subject to several caveats. First, as noted, ecosystems may require some minimum area for long term survival, which implies that the value function would need to tend to infinity as it approaches that minimum value (rather than as it approaches to zero as shown on Figure 8.2).

Second, and perhaps more importantly, the argument is sometimes made that the value to be ascribed to the loss of habitat associated with some regulatory or governmental decision depends upon whether what remains is secure. For example, the cost of the loss of 1 ha of a habitat if 1,000 ha remains might be valued as negligible, if that remaining habitat is protected from encroachment. On the other hand, if the remaining 1,000ha is vulnerable to encroachment, then the loss of that 1 ha under consideration might be assigned a much higher value.[4]

Such reasoning is not logical, because there is a confusion between costs and benefits. On the cost side, it really does not matter whether the loss is attributable to a power plant, or to agricultural development, or even to illicit felling: the loss is the same in both cases. On the other hand, the benefits to society of these two activities may be quite different. Yet it is only land use planning at the local and regional level that can address the costs and benefits of alternative uses in a systematic way.

In any event the difficulties of estimating the appropriate value function prove to be largely moot (for the power sector), insofar as the fraction of remaining areas of each ecosystem that might be consumed by power sector projects is extremely small, meaning we are on the very far right hand side of the curve of Figure 8.2, where the slope is essentially flat. Consequently for numerical computation this element can simply be represented by the area lost.

Thus the biodiversity index associated with site i, B_i, is therefore simply defined as

$$B_i = \sum_i A_{ij} w_j \tag{8.4}$$

where A_{ji} is the ha of ecosystem of type j at site i
w_j is relative biodiversity value of type j (as defined in Table 8.2).

As it turns out, it appears that the biodiversity index is strongly correlated with reservoir size, as indicated on Figure 8.3. This is simply a consequence of the fact that all of the larger projects inundate relatively large amounts of natural forest of high biodiversity value: this would not necessarily be the case elsewhere.

However, when one excludes the five very large projects with reservoir sizes in excess of $15 Km^2$, the correlation is quite poor, reflecting the diversity of ecosystem types encountered at the smaller projects (See Figure 7.4).

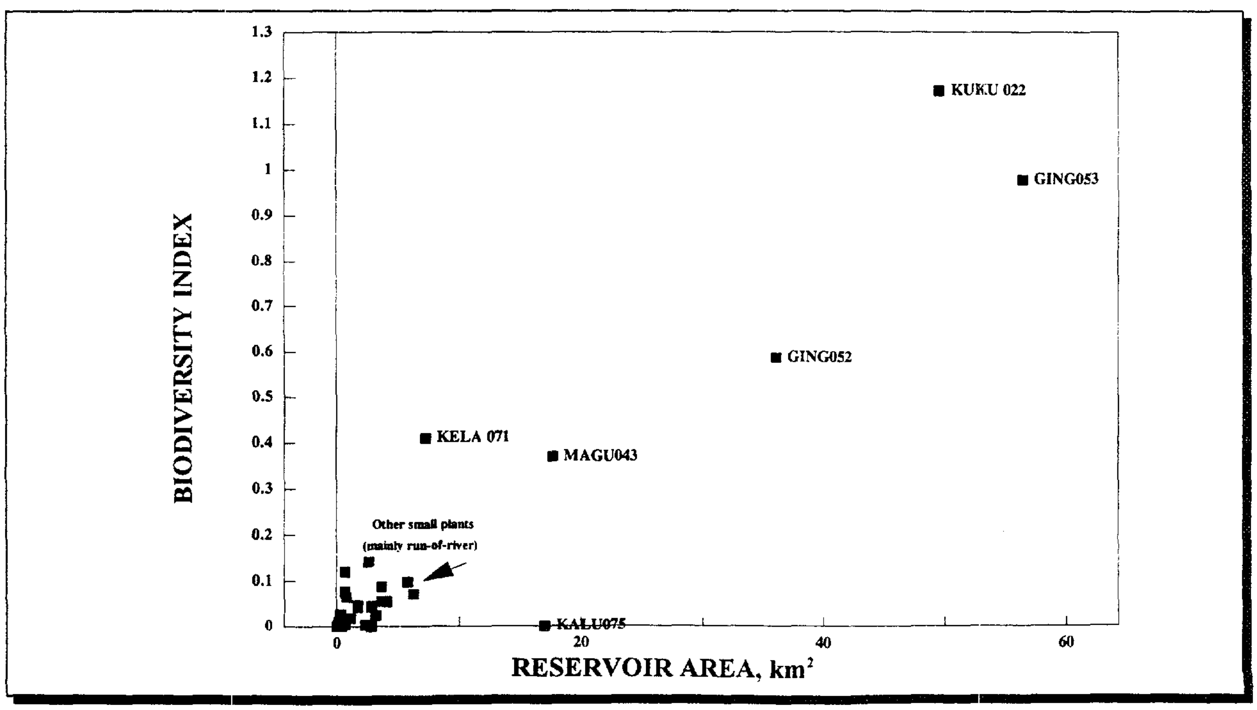


Figure 8.3: Biodiversity index value and reservoir area

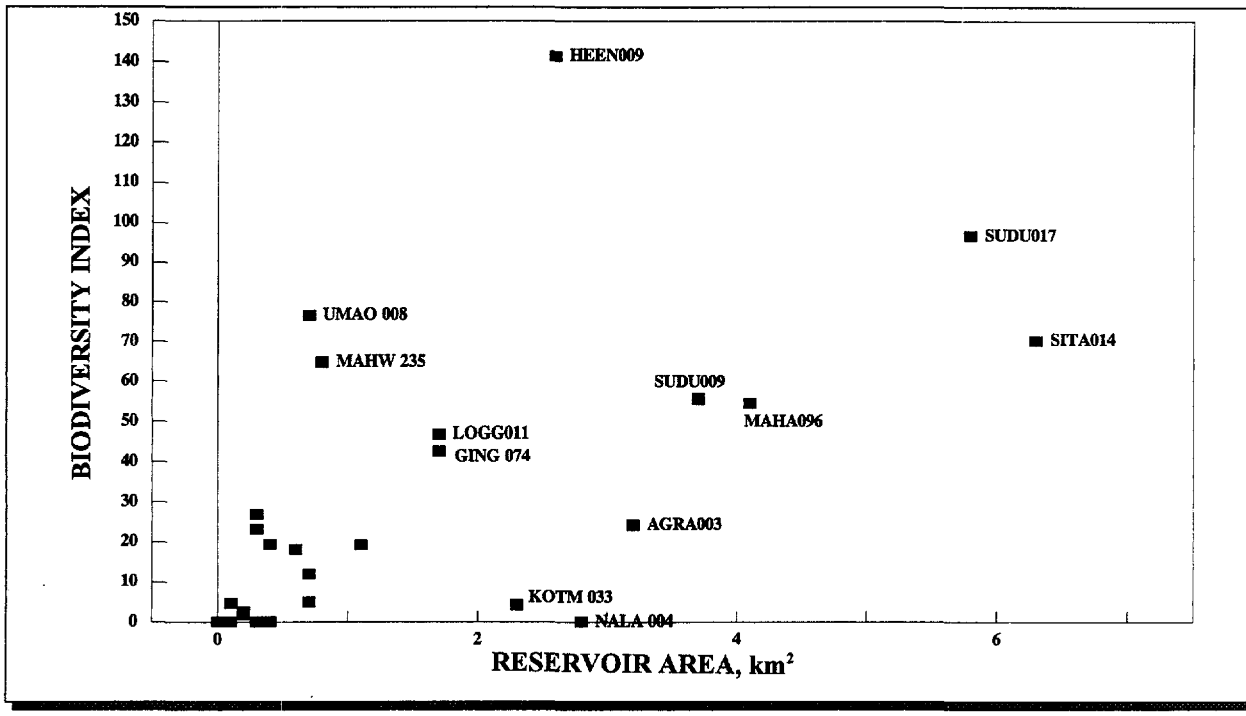


Figure 8.4: Biodiversity index value and reservoir area at the smaller hydro projects

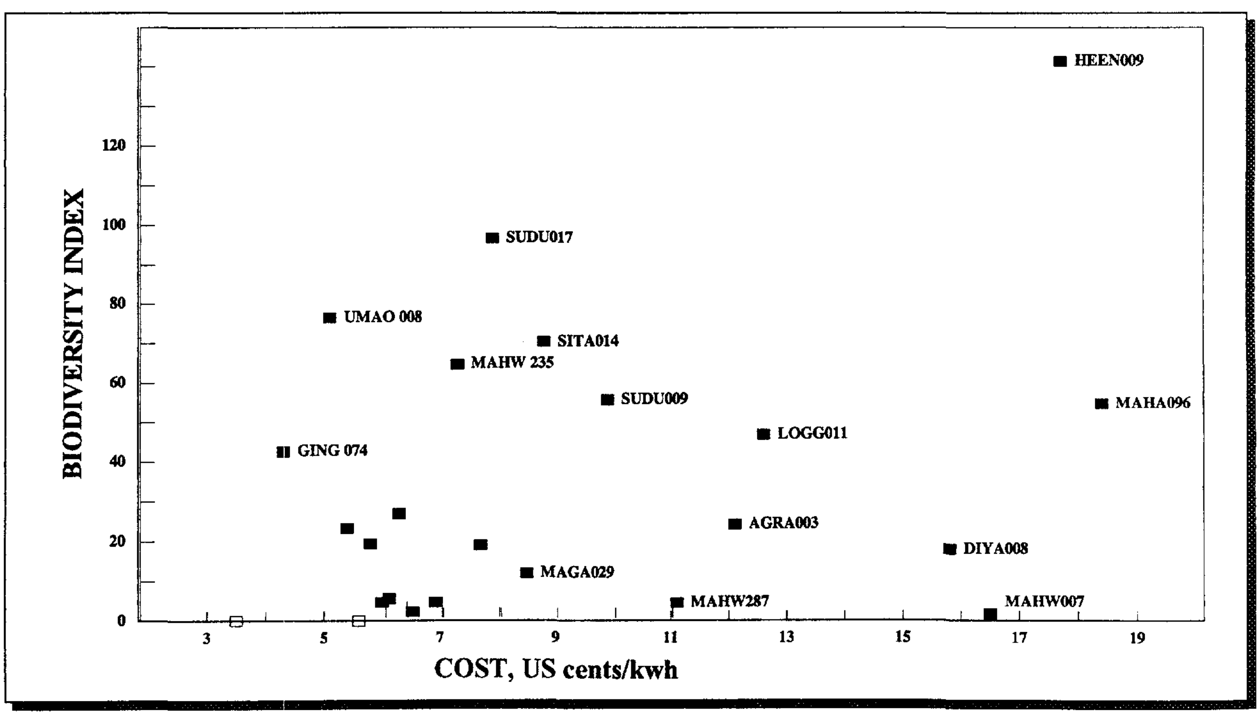


Figure 8.5: Relationship between biodiversity index value and project cost

Finally, on Figure 8.5 we show the relationship between the biodiversity index and project cost (in cents/kwh), (where project costs include costs of resettlement and the opportunity costs of lost production): once again there is little correlation.

Air quality and acid rain

Detailed air quality modelling studies were conducted for the Trincomalee EIS. The consultants used the ISCST air quality model developed by the United States EPA to estimate ground level ambient concentrations of SO_2, particulates and NO_x; estimates were made for annual average, maximum 24-hour, and maximum 3 hour concentrations. Such modelling is fairly standard procedure for demonstration of regulatory compliance.

One of the major problems in using sophisticated air quality models is the need for detailed meteorological data; in the case of Trincomalee site the consultants elected to use data from Guam. Although this procedure was criticized extensively at the time, in our judgement this was not unreasonable.

Much more important is the question of whether the calculation of the increase in ambient concentrations of pollutants says anything about the impacts. Consider, for example, the map of Figure 8.6, which shows the maximum 3-hour SO_2 concentration: the maximum concentrations are seen to lie to the northwest of the plant; even for a 600Mw plant, the indicated maximum value

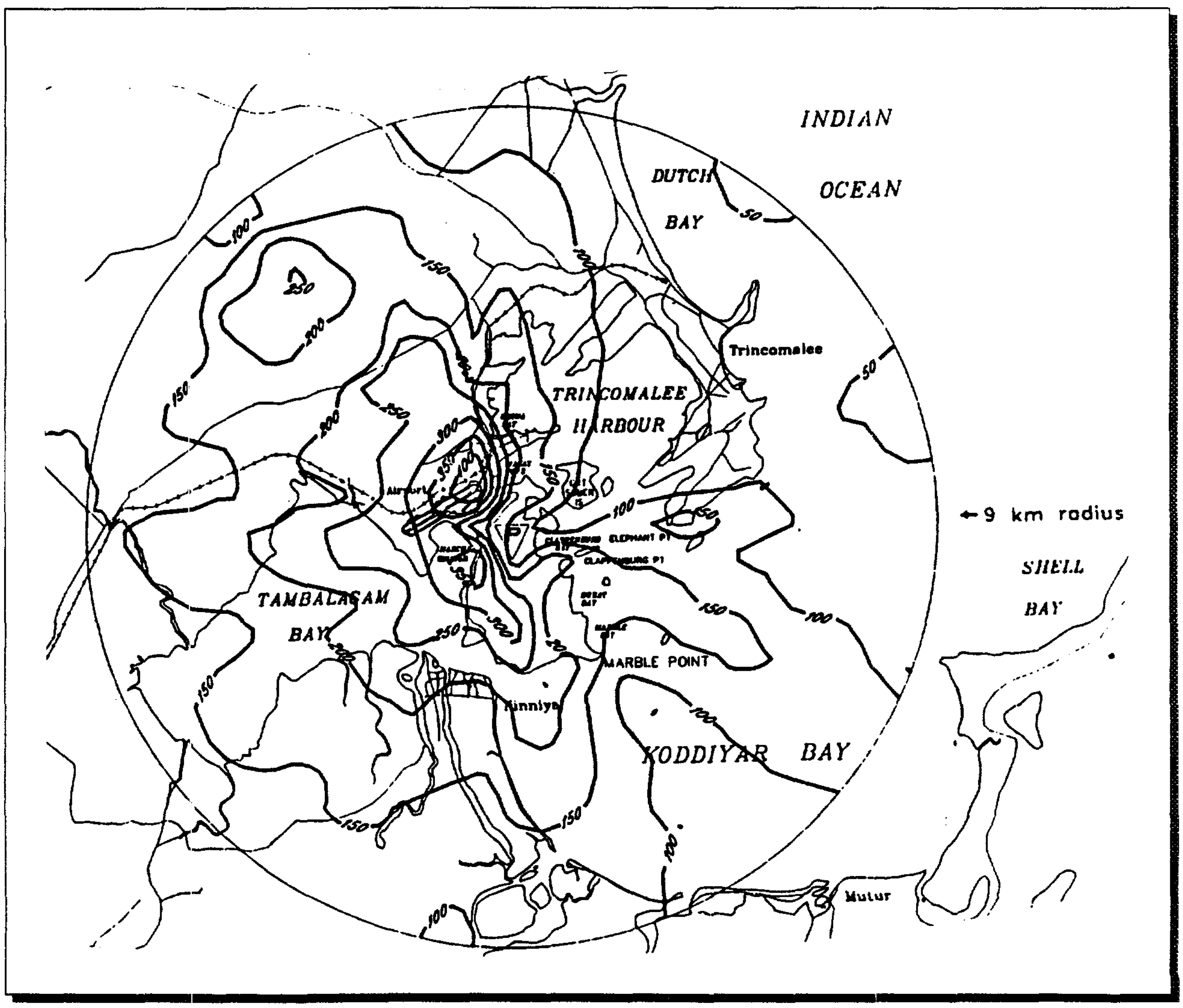


Figure 8.6: Maximum 3-hour SO_2 concentrations.

is well within the standard (567ug/m^3 compared to the U.S. standard of 1,300 ug/m^3).

Yet from an impact standpoint, this may not be the critical period, since the number of people who live in this area is quite small. The worst case from a population exposure standpoint would be when the prevailing winds are weak and from the Southwest, during which times concentration maxima would be expected on the opposite side of the bay in the main Trincomalee city area. This might be not the absolute worst 3-hr period (which is the usual regulatory standard), but perhaps the 10-th worst, or the 50-th worst. It is an excellent example of the difference between attempting to estimate actual environmental impacts and performing computations designed largely for regulatory convenience.

In sum, it is clear that the efforts to date to quantify air quality impacts have been very limited. The "air quality" scales used in the thermal options study are nothing more than very crude approximations of judgments of "siting experts", and are not very likely to be related to actual impacts. Even the more sophisticated modeling studies of the Trincomalee EIS tell us nothing about impacts; they are relevant only to the question of whether ambient standards are likely to be exceeded.

Finally, there are some rather troubling concerns about the extent to which air quality models developed in the United States, and used routinely for regulatory purposes there, are in fact valid for the very different meteorological regimes of tropical and monsoonal climates. We know of no study that has validated the predictions of these air quality models in tropical countries through rigorous field measurements.

Acid Rain

As noted in Chapter 4, acid rain is likely to become an increasingly important regional issue in Asia. While the total emission level of acid rain precursors (SO_2 and NO_x) from sources in Sri Lanka is likely to play a negligible role in the overall regional picture (especially by comparison with emissions in India), we held it still to be useful to include a comparison of alternative policy options with respect to total emissions of these pollutants. Again the calculated index is simply the discounted value of annual emissions.[5]

For the moment, absent any particular evidence for Sri Lanka to the contrary, we have assumed SO_2 and NO_x to have equal weight. We recognize that among the different attributes considered here, this has the most tenuous correlation with actual acid rain impacts likely to be encountered in Sri Lanka as a consequence of power sector emissions; clearly further research, and above all adequate baseline air quality and rainfall pH monitoring data, is the fundamental prerequisite for more credible assessments of any acid rain impacts to become possible.

Health impacts

There are two categories of health impacts that are of potential importance: those associated with hydro plants, which are largely associated with waterborne diseases, and those associated with thermal plants, which are largely related to the exposure to increased ambient levels of airborne pollutants (such as SO_x, NO_x and fine particulates).

Although the potential health impacts of hydro projects are discussed in the GTZ Masterplan, quantification is exceptionally difficult. The main concern is malaria, which has seen a resurgence in recent years despite its near eradication in the late 1960s. However, although the number of cases has risen, the death rate has fallen to almost zero, as a result of improved medical treatment.[6] There are some indications that the resurgence of malaria is related to the implementation of new irrigation areas, but there are no definitive studies. The extent to which small pools of standing water in the largely dry riverbed downstream of dams are linked to malaria is also unknown, except that these certainly represent, in theory, excellent breeding grounds for mosquitoes.

While the costs of spraying (the GTZ study cites 1985 expenditures in Sri Lanka for Malathion at Rs 77.8million), and treatment (estimated at Rs5 for each of slightly over 100,000 patients in 1985) are readily established, the number of malaria cases that can be predicted for specific hydro projects where stagnant riverbed water pools are not regularly flushed out is essentially impossible to estimate. At the Victoria dam there has been some discussion of maintaining downstream flows to an average of $3.5m^3$/sec, and to equip the dam with a small powerhouse to generate power at the dam itself. However, a rigorous benefit/cost evaluation does not appear to have been conducted.

To date the attempts to quantify air quality impacts associated with different thermal generation technologies and with different sites in Sri Lanka have been very crude. "Air quality" was one of the attributes used in the Black and Veatch thermal generation options study: alternative sites were assigned an air quality score in the weighting summation method that was used to select sites for different generating stations.

The most serious problem with such expert judgement scales is not that expert judgement may be incorrect, but that the relationship between the score and possible mitigation actions is not demonstrable. In other words, there is no way of subsequently performing a sensitivity analysis that might explore the use of alternative fuels, alternative pollution control strategies, or of alternative technologies.

For the purposes of this case study, we make a much more precise calculation, by estimating the actual population exposure, namely

$$X = \Sigma C_j P_j \qquad (8.5)$$

where X is the cumulative population exposure
the incremental ambient concentration attributable to the power plant
Pj is the population in the j-th grid square[7]
Cj is the incremental average annual concentration in the i-th square, attributable to the emissions from the source in question.

The model is run for some given number of wind direction and wind speed combinations. For example, one may run the model for 16 directions and 3 different wind speeds, for a total of 48 "plumes": since concentration is non-linear with wind speed, use of average wind speeds in each wind rose direction may introduce bias. In our study we used two wind speeds for each of 16 directions. The total concentration in square j, C_j is then simply the sum of the individual plume contributions:

$$C_j = \sum_k c_{jk} \qquad (8.6)$$

where c_{jk} is the incremental contribution in square j attributable to the k-th plume, which is in turn given by[8]

$$C_{jk} = \frac{Q}{\pi u_k \sigma_y \sigma_z} e^{\left(\frac{y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2}\right)} \qquad (8.7)$$

where u is the wind speed (in meters/sec) of the k-th plume
Q is the source term (in g/sec)
H is the stack height (in meters)

It is important to state the implied assumptions involved in the definition of such an attribute as a measure of health damage. Most important is the assumption that the dose-response function is linear through the origin: neither thresholds nor non-linearities are assumed; this is equivalent to saying that one individual experiencing a dose of two units has the same impact as two individuals experiencing a dose of one unit each. In fact of course it is reasonably well established that acute episodes of high pollutant concentration, even of short duration, are much more damaging, particularly to the aged already suffering from respiratory ailments, than chronic exposure to lower levels. Nevertheless, whatever the limitations of the simple linear model implied, the main issue is whether the procedure as a whole provides a more objective way of comparing the potential air quality impacts of alternative sites, technologies and pollution mitigation strategies than the purely subjective assessments of "air quality impact" of the type usually made in siting studies (as already presented in our discussion of the BVI Thermal Options Study).

To be sure, this model is no substitute for detailed air quality simulations that might be conducted at the EIS stage to demonstrate compliance with specific regulatory requirements. But for application to system planning and site selection studies we believe the model to be a material improvement over the sort of purely subjective "expert judgement" scale commonly encountered.

The model is implemented in a Lotus 1-2-3 spreadsheet: stack height, plume rise and pollutant emission rates are user defined. The dispersion coefficients are calculated endogenously according to user-specified stability conditions.

The question of whether or not it is permissible to use surrogate meteorological data is difficult to answer. Certainly in some cases there seems to be agreement that the errors involved in using surrogate site data are small -- such as in the U.S., where large areas of the country are subject to very similar weather patterns[9]. But the validity of using Guam data in Sri Lanka, as did BVI in the case of Trincomalee, has yet to be demonstrated, and certainly needs further study for detailed, project specific air quality modelling work. However, for our simple air quality model, that is appropriate to the planning stage where great precision at a single site is less important than being able to make valid comparisons between sites and between technologies, such data issues do not arise[10].

Figure 8.7 shows the results of some basic calculations in which we varied the stack height for the three sites, and calculated the annual average population exposure for an emission rate of 1Kg/sec of SO_2 (which corresponds to that of a 900Mw plant burning 1% sulfur coal). BVI estimated the so-called good engineering practice (GEP) stack height at 135m, which is adopted in this case study for the base case.

As one would expect, to the extent that these calculations are only for a 10km radius around the plant stack, increases in stack height have a much greater effect in densely populated areas (such as the Sapugaskanda site near Colombo) than in lightly settled areas (such as at Matara) (See Figure 8.7). Clearly it would be very desirable to extend the radius of impact calculation to beyond the 10km radius used here; obviously the greater the radius examined, the smaller is the impact of stack height. Indeed, this illustrates an important difference between air quality modelling conducted to assess compliance with ambient standards, for which indeed any

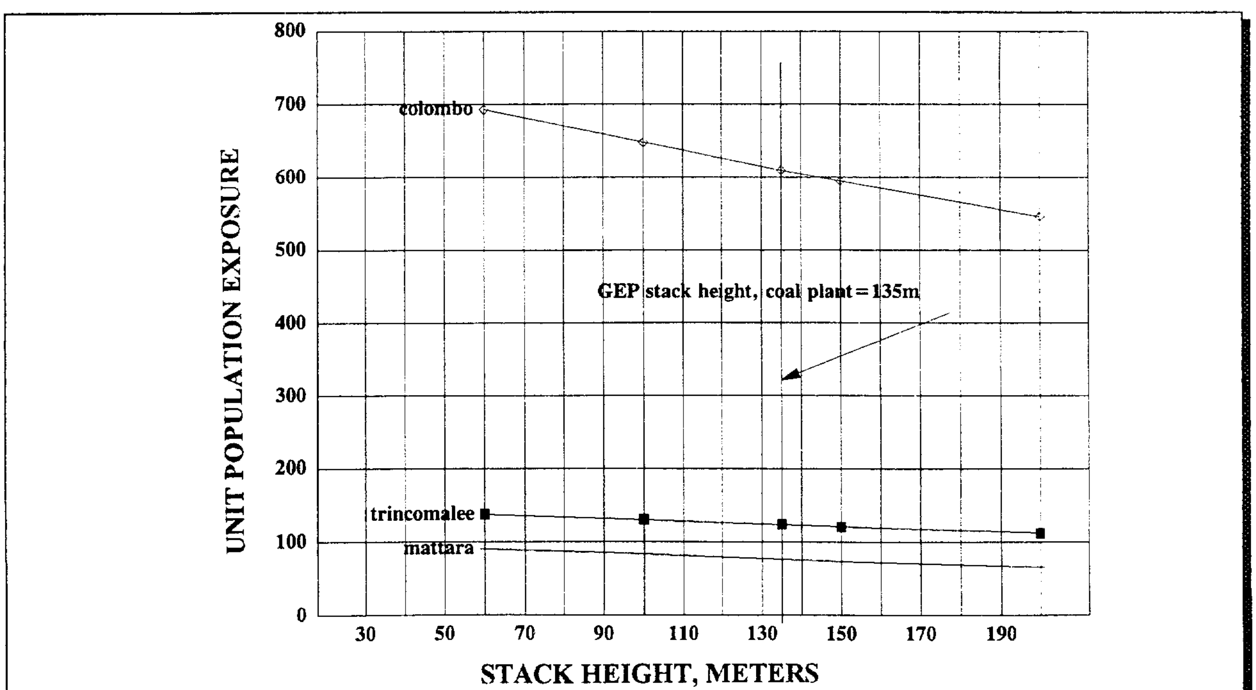


Figure 8.7: Unit population exposure to SO_2

maximum values generally lie within a 5-10km radius, and air quality modeling designed to assess impacts.

A further problem concerns the extent to which the presence of a major power plant itself acts as a growth pole, and attracts additional population. Clearly for major cities this is not likely to be an issue, and can safely be ignored for Colombo. However, for both the Trincomalee and south coast sites, it is conceivable that population may grow faster than would otherwise be the case in the absence of any major power plant. In light of the difficulty associated with making local area population projections, fine tuning the population estimates would be a somewhat specious exercise, and the population estimate for each area was therefore simply taken as constant.[11]

Nevertheless, despite these shortcomings,[12] the population exposure indices do provide a much more objective measure of potential air pollution impact than purely subjective assessments of "air quality" as used in the BVI siting studies. It follows immediately from the Figure 8.6, for example, that reducing SO_2 emissions in Colombo (say at the Sapugaskanda diesel plant) by 1 kg reduces health damages by about 7.5 times more than a corresponding reduction of 1Kg at the Matara site. This comparison is unambiguous. By contrast, it is unclear what can be inferred from the ratio of "air quality" scores in the BVI thermal options study (see Table 7.2), where the ratio of scores for Sapugaskanda and Matara is 11:29.

Solid wastes

Coal burning power plants generate substantial quantities of solid waste, namely ash, and, in the case of FGD systems, of scrubber sludge. The conventional representation of the potential extent of problems related to disposal of these wastes is to estimate either the tons of waste generated, and/or the amount of land necessary for disposal -- indeed, as already shown on Figure 1.2, the GTZ masterplan software used in Sri Lanka generates solid waste quantities in this form.

In fact neither the quantity of waste produced, nor the amount of land consumed, represent appropriate attributes. The cost of land necessary for solid waste disposal is generally well known, and is included in the site development costs, and hence readily quantified. The opportunity costs of any lost production can be handled in the same way as discussed for hydro reservoirs; they are readily quantified and included in the economic analysis.

The real environmental issue that requires separate quantification relates to the risk of contaminating groundwater from toxic leachates, or of run-off entering nearby surface waters. A valuation of this risk would of course also need to take into account what uses were being made of the aquifers in question. For example in many areas on the south coast, such as the Matara area that is one of the sites under consideration for a coal burning power plant, salt water intrusion has already made many coastal aquifers sufficiently brackish to preclude their use for drinking water, and municipal systems are being extended to provide local villagers with drinking water.

Development of an appropriate attribute scale follows directly from the physical laws in question, namely, in the case of flow through porous media, Darcy's Law:

$$Q = k\ A\ dh \tag{8.8}$$

where Q is the flowrate through the soil
k is the coefficient of permeability
A is the cross sectional area of soil through which flow occurs
dh is the hydraulic gradient, equal to the difference in head divided by the length of the drainage path.

The term that is likely to dominate this equation is the permeability, for it varies by almost 10 orders of magnitude from the most porous sands and gravels to the least porous clays (see Table 8.3). Since the other terms in this equation do not typically vary by orders of magnitude, the main part of the risk involved is given directly by the permeability of the soils in question. The soils maps available for Sri Lanka appear sufficient for a determination to be made both of the soil at

Table 8.3: Permeability of major soil groups

soil type	permeability k, [1/cm]
coarse sand	0.4-3
medium sand	0.05-0.15
fine sand	0.004-0.02
silty sand	10^{-5}
sandy clay	10^{-5}-10^{-4}
silty clay	10^{-5}
clay	10^{-6}

the site, as well as the availability of impervious soils near the site that may be suitable as liners.

In practice, the permeability of that layer that has the lower permeability will be the governing factor in leachate generation: in the case of a sludge landfill, it may be the permeability of the sludge itself that governs, or the permeability of the soil, or, in the event necessary, by the layer of relatively impervious soil used as cover or as a bottom layer. Thus, even if the site itself is not a low permeability soil, the availability of suitable soils in the neighborhood of the site, which can be used as an impervious liner, can be used as the controlling measure.[13]

Of course once detailed feasibility studies are available, the actual probable risk even in high permeability areas can be attenuated by mitigation measures (such as using impermeable liners), to the point at which the expected value of aquifer contamination is no greater than at a site where more impermeable soils may not require liners. However, what is important at the planning stage is simply to highlight areas of potentially significant risk, and to ascertain whether there are sharp differences between sites and between policy options that need attention at the siting study stage.

Aquatic ecosystem impacts

The valuation of potential environmental damages from thermal discharges is extremely difficult. The most important problem is that it is very difficult to extrapolate from one aquatic environment to another. Thus, for example, even if there were available a reliable study on the impact of thermal discharges on the coral reefs off Australia or the Red Sea coastline off Egypt, it would be unclear what applicability such studies might have on the unique conditions of Sri Lanka.

To be sure, certain general principles are well established: water temperatures off the coast of Sri Lanka are already fairly close to the known lethal temperature thresholds for corals. But predicting the impact of some specific temperature rise from a specific thermal source is extremely difficult if not impossible based solely upon model results.

Moreover, the current set of standards are of little guidance: the present requirement is only that no discharge may be of greater temperature, at the discharge point, than 45°C; the design temperature of the once-through cooling system discharges for Trincomalee was set by BVI as 37°C, which is well below the standard -- a fact that is repeatedly mentioned by the EIS.[14] However, the basis for a 45°C standard even for small volume industrial effluents is unclear.

The general effects of thermal discharges into coastal waters are of course well recognized. Discharges into the well-mixed, surface layer would have usually have the general tendency to repel fish. On the other hand, if the discharge is below the thermocline, thermal discharges would have a generally beneficial effect, as the up-welling effect caused by plume buoyancy brings nutrients into the layers nearer the surface.

However, attaching specific numerical estimates to the values of this general function is essentially impossible. It is simply not possible to be able to make statements of the type that a 1°C average surface temperature increase over an area of x km^2 would cause fish-catches to decline by y %.

What can be done as a generic calculation that can be used to compare different sites is to begin with a definition of what is considered to constitute an acceptable environmental risk; for example, say a temperature increase of no more than 1°C at the surface. One then calculates the surface area over which this criterion is exceeded as a function of the cooling system design proposed.

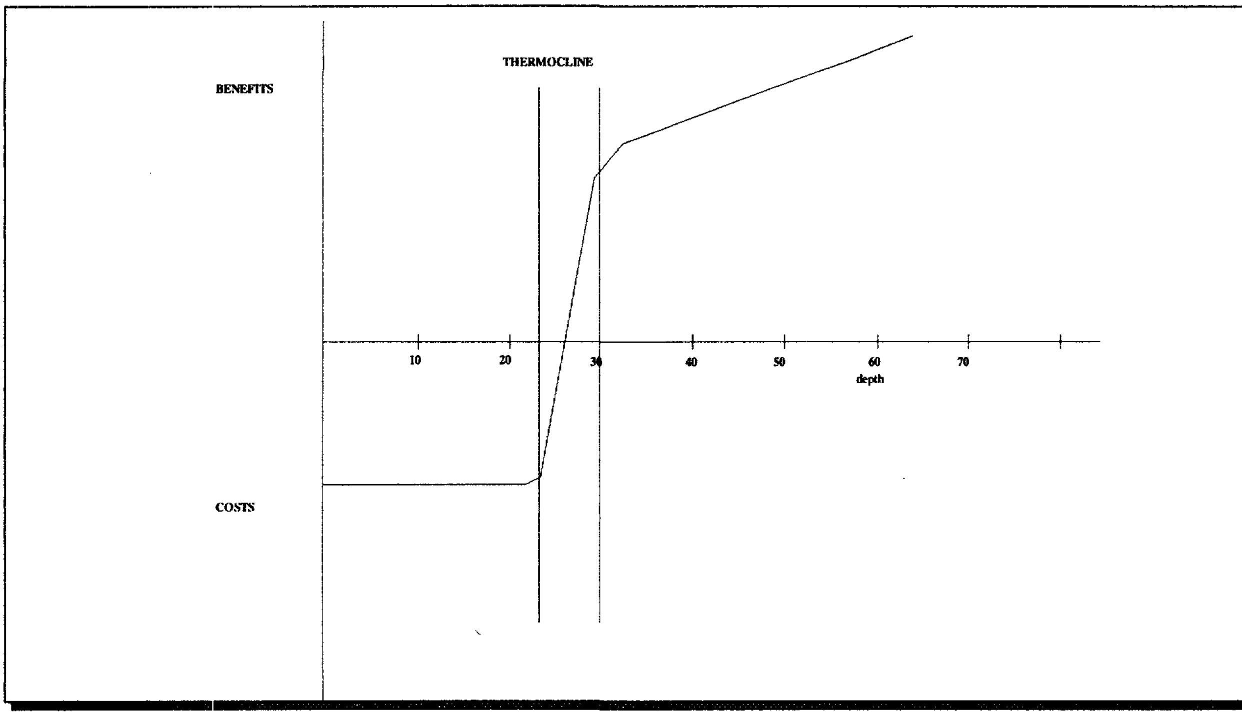


Figure 8.8: General functional form of the aquatic ecosystem damages.

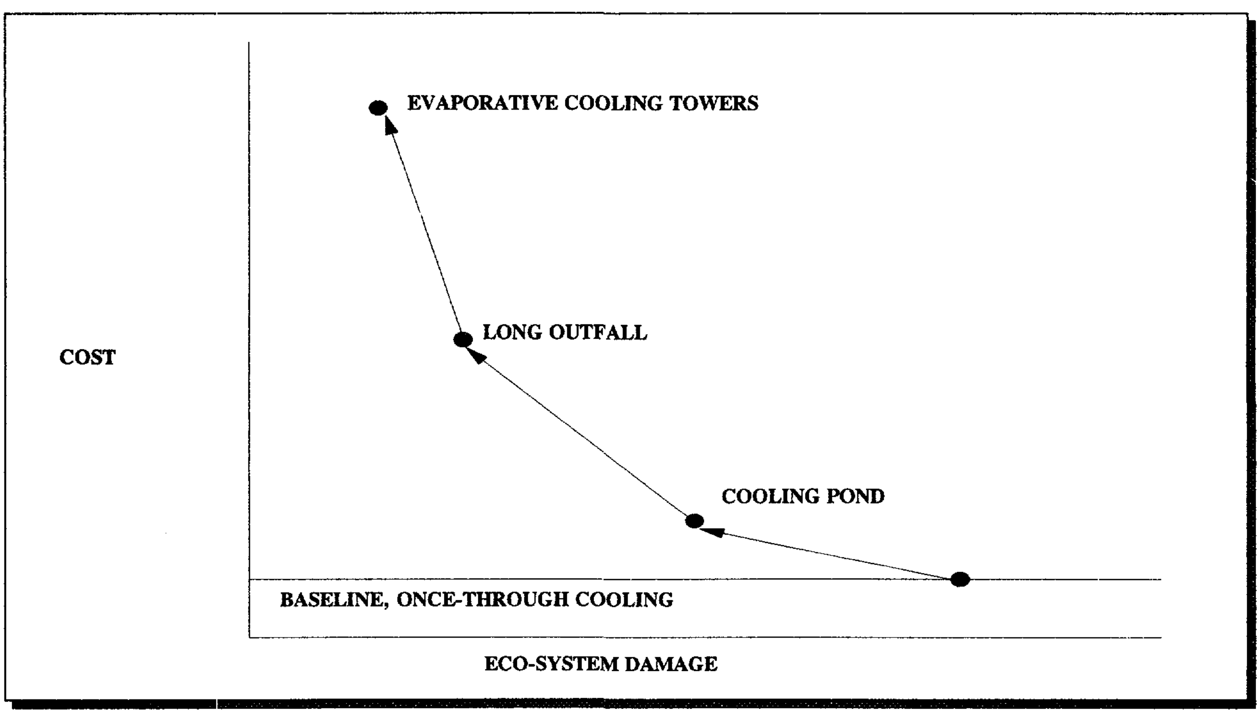


Figure 8.9: Thermal impact trade-off curve

Table 8.4: Cooling system options

option	application/issues
once-through cooling, direct discharge	as proposed at Trincomalee
once-through cooling with long ocean outfall and diffuser system	e.g. San Onofre, California and St. Lucie in Florida. Additional costs very difficult to estimate absent detailed site studies.
natural draft saltwater cooling tower	a single tower about 400ft high would serve a 600 Mw plant. Some efficiency losses (about 5%), new issues of visual intrusion (from both the tower itself and the associated plume) and salt drift over land. Blowdown discharge about 5% of the equivalent once-through cooled flow;treatment may be required because of high concentrations of anti-fouling agents. Net heat load to the bay would be about 3% of the once-through cooled version.
mechanical draft cooling towers	attractiveness relative to natural draft towers strongly dependent on local meteorological conditions.
natural draft cooling tower using makeup water from local aquifers.	salt drift problems would be greatly reduced: feasibility of adequate groundwater supplies in the vicinity of Trincomalee Bay unknown. (At some U.S. plants, it has been proposed to use sewage treatment plant effluents as makeup water, but sewage quantities from the City of Trincomalee would be insufficient).
cooling lake (or canal system)	eliminates the visual intrusion impacts of natural draft towers. Significant additional land area required (about 1000 acres for 1000Mw). Costs high, particularly if vinyl liners must be used to prevent seepage (however local aquifers may already be brackish, as on the South Coast).
dry cooling towers	zero thermal discharge to the bay; capital costs roughly twice those of evaporative cooling towers. However there are also serious losses of thermal efficiency, as high as 15% over the basecase. Considered techno-economically feasible today only for smaller peaking/intermediate plants.

The fundamental issue is whether or not cooling system configurations other than once-through cooling ought to be considered. As noted previously, discharge of once through cooled waters into well-mixed shallow bay waters of Trincomalee Bay was considered to involve an unacceptable degree of impact on aquatic ecosystems, despite the consultant's assertion that the impacts were "negligible".

What in fact are the alternative cooling system configurations that might be considered?[15] These are listed on Table 8.4; although the alternatives to the base case configuration all reduce the thermal impacts and involve higher costs, some of them also introduce new environmental impacts. While a detailed engineering study of these alternatives is clearly beyond the scope of this case study, in our view the potentially most suitable alternative is some kind of long outfall with diffuser system, perhaps

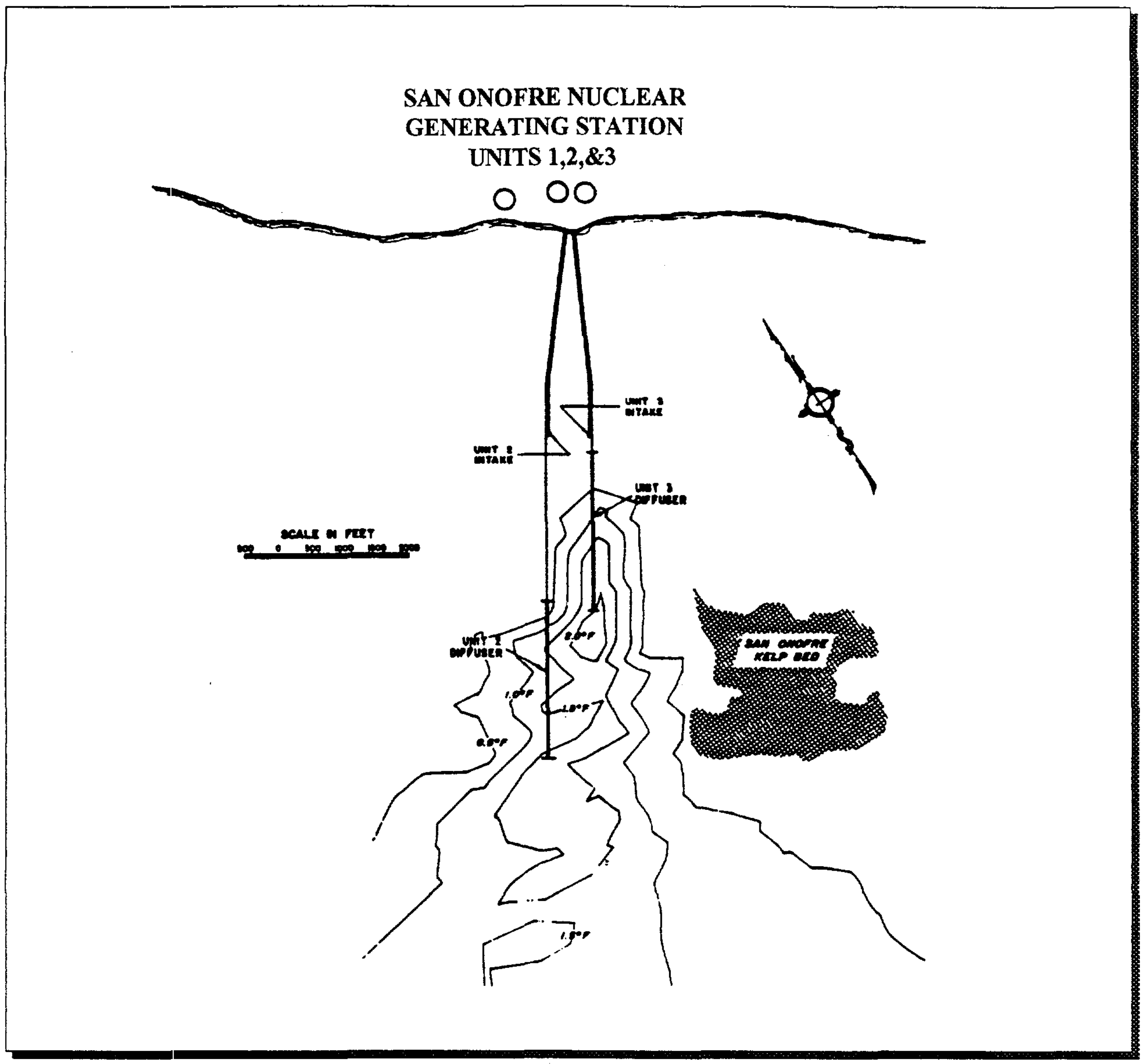


Figure 8.10: Outfall and diffuser system configuration at the San Onofre plant

involving a different site to that recommended by BVI, but with discharge to the much deeper waters of Koddiyar Bay.

That such long ocean diffuser system outfalls are technically feasible is illustrated by a number of power plants in the United States.[16] On Figure 8.10 we illustrate the design for the San Onofre power plant in California. The intake is about 1 km off-shore, while the diffuser discharge section on the outfall starts about 2 km offshore and extends for about another km.

To be sure, such a system involves additional costs. However, the alternative of moving the coal plant to the South Coast also involves very severe fuel cost penalties. We estimate the present value of the incremental fuel costs for 900Mw over a 30 year lifetime of the plant at $US142 million,[17] whereas the incremental costs of a diffuser system are likely to be in the range of $25-50million.

The thermocline is generally located at around 50 meters, and significant advantages might be obtained by discharging at such depths. On Figure 8.11 we show the bathymetry of Trincomalee Bay, highlighting the 50-meter isobath. The site recommended by BVI is

Figure 8.11: Bathymetry of Trincomalee Harbor

identified on this map as "SITE 2A". Also indicated are the coal port alternatives (P3A, P3B, etc).

From the standpoint of proximity to such deeper waters, it is evident that Site 3A would require an outfall of about 2000meters, roughly eastwards from the site, to reach such depths (in the same direction as the coal unloading facilities P3A, P3B). In the discussion concerning coal unloading facilities, BVI notes no unusual construction problems that might be indicative of difficulties associated with the construction of a long outfall/diffuser system : the conveyer system envisages the use of tubular steel piles driven into the sea-bed.[18]

Whether or not such an option is in fact feasible requires an engineering evaluation that is beyond the scope of this research study. Certainly an evaporative cooling tower is technically feasible at either site 2A or 3A. Our point is that a reasonable set of mitigation options should be considered in some detail, costed out, and environmental modelling conducted for each of these options. This should be done for a few representative sites even for national scale analysis, given the clear importance of the issue. In the Trincomalee EIS, the only thermal effluent modelling presented was for the once-through cooling option at site 2A.

Employment

Employment creation is an important objective of national policy, and in Sri Lanka there has occurred frequent discussion of the need for employment creation in the South where youth unemployment rates are especially high. It should be noted at the outset that what is captured in this attribute is the separate and purely political objective of employment creation, and is to be distinguished from strictly economic benefits that would captured by the use of shadow wage rates appropriate to reflect high unemployment in the construction cost estimates.

The employment creation attribute used in this study is based on the estimates of local construction and operating phase employment impacts developed as part of the GTZ Masterplan. The total man-year construction phase impact is spread uniformly over the construction period; all employment data are then discounted to calculate the following index:

$$E = \sum_t \frac{\Sigma (C_{tk} + O_{tk})}{(1+r)^t}$$

where O_{tk} is the number of operational staff required in year t at the k-th facility, C_{tk} is the number of persons employed during the construction phase at the k-th facility in year t, and r is the discount rate. It is implicitly assumed that the nominal value of each person employed is the same across time periods (before discounting). This corresponds to the democratic political objective of the attribute -- again as noted above, wage rate differences among employees is captured in the economic attribute by appropriate wage rate computations. Finally, in fact the bulk of the additional jobs created are for semi-skilled workers and new jobs for unemployed.[19] The opportunity costs of such job creation are near zero, given that both the Trincomalee and South Coast regions suffer from very high rates of unemployment (in excess of 30% for unskilled young males).

The economic attribute

Presently the CEB uses the following measure to evaluate alternative generation options: the net present value of total system costs (capital and operating costs of new facilities plus operating costs of existing facilities) over the next 15 years is divided by the present value of generation requirements over the same period less the present value of generation from existing hydro. This measure is a good approximation for the average incremental cost (AIC) of generation (since in the average hydro year, the current energy demand is almost exactly met by the existing hydro plants).

However, for our study this is not the appropriate criterion, insofar as some of the policy measures examined here reflect improved demand side measures and improvements in T&D losses. Therefore, in order to provide for a valid comparison of supply and demand side measures, the appropriate numeraire is incremental energy demand at the consumer;[20] the result is an estimate of the AIC of meeting incremental demand (which will be somewhat higher than the AIC of generation because of T&D losses). For example, for the CEB base case system expansion plan, the ENVIROPLAN model estimate of the AIC of demand is 5.81c/kwh, while the AIC of generation is 5.65c/kwh. The latter is very close to the CEB's estimate of 5.61c/kwh.

Notes

[1] Actually the chemistry is quite complex, involving many intermediate species. The sorption of SO_2 in a scrubber takes place by dissolving gaseous SO_2 in the alkaline scrubber slurry to form the soluble species sulfite and bisulfite

$$2H_20 + SO_2 <=> SO_3^{2-} + HSO_3^- + 3H^+$$

[2] A species is said to be endemic to Sri Lanka if it occurs nowhere else in the world.

[3] *Calculation of environmental costs and benefits associated with hydropower development in the Pacific Northwest*, Bonneville Power Administration, Report DE-AC79-83BP11546, Portland, Oregon, April 1986.

[4] Although not often put explicitly in these terms, this line of reasoning has in effect been much used by environmentalists to oppose power facilities. For example, the reasoning goes, because coastal wetlands are ecologically valuable, power plants should be sited elsewhere. Yet in fact a much greater threat to coastal wetlands is posed by uncontrolled real estate development, but since this is harder to control, attention is focussed on power plants that make much easier targets for attack.

[5] An international collaborative project called "Rains-Asia" is currently underway to develop a strategy for acid rain and emissions reduction in Asia. This will apply a pioneering acid rain model developed for Europe (RAINS) to Asia. The project is being coordinated by the World Bank, and involves a number of participating institutions in Asia. Results reported at a first workshop in September 1993 suggests that the main areas affected by sulfur deposition in Asia are China, Taiwan, Korea, Japan and Thailand. According to the preliminary emissions inventory complied by this study, India presently has SO_2 emissions of some 5 million tons/year, while those in Sri Lanka are estimated at 89,000 tons/year (with zero emissions from the power sector)

[6] Unfortunately <u>plasmodium</u> <u>falciparum</u> has recently developed resistance against chloroquin treatment.

[7] Populations were estimated for each 500x500 meter grid square using census data and land use maps. Unfortunately, detailed land use maps were not available for the Trincomalee area, and therefore the population data was estimated on the basis of very crude approximations that have limited reliability.

[8] For a good recent text on air pollution modeling, see e.g. P. Zanetti, *Air pollution modeling: theories, computational methods and available software*, Van Nostrand Reinhold; New York, NY, 1990.

[9] For example, the U.S. Nuclear Regulatory Commission, in its Guidelines for Regulatory Analysis states that "..plant specific meteorological inputs are not critical ... except for a few sites, the distribution of stability, wind speed and direction during a year does not vary widely within most of the United States. Thus the meteorological data from a mid-west site would be a reasonable representation of a typical site that could be used in most analyses".

[10] Calibration tests of our model against that used by BVI at Trincomalee, and the model used in the EIS at Lakhra, Pakistan, showed our results to be within 10% for annual averages.

[11] Clearly, a far greater component of error is the unavailability of detailed population data for Trincomalee even for the present, and shortcomings of the meteorological data. Once these deficiencies can be addressed, introducing the dynamics of population growth may then become useful.

[12] Among the other simplifying assumptions is that of flat terrain (which at least for the immediate vicinity of most of the coastal locations considered in Sri Lanka is not unreasonable, with no significant hilly terrain with at least 20-30km), and neglect of wet deposition (also not too serious insofar as both the south coast and Trincomalee sites are relatively dry for most of the year, and during the monsoon season, when most of the annual rainfall does occur, wind speeds are generally quite high, ensuring good dispersion and low ambient concentrations in the near field.

[13] Nevertheless, this still assumes that liners do not fail due to cracks and punctures, which is the most common failure mode: and indeed the impact of a failure of a highly impervious liner over a pervious soil may be greater than the risk associated with a relatively less pervious soil without a liner.

[14] For example "...it should be noted that the design conditions for thermal discharge were based upon the standard set by CEA that stated maximum discharge temperature was limited to 45°C. As a mitigation measure the power plant is designed for a maximum discharge temperature of 35°C(with 37°C as a worst case situation), which allows for a significant safety margin" (Trincomalee EIS, Volume I, p.8-51).

[15] Many of the Environmental Impact Statements prepared for the U.S. Nuclear Regulatory Commission have excellent discussions of the advantages and disadvantages of alternative cooling system configurations. These discussions apply equally to fossil fired power plants.

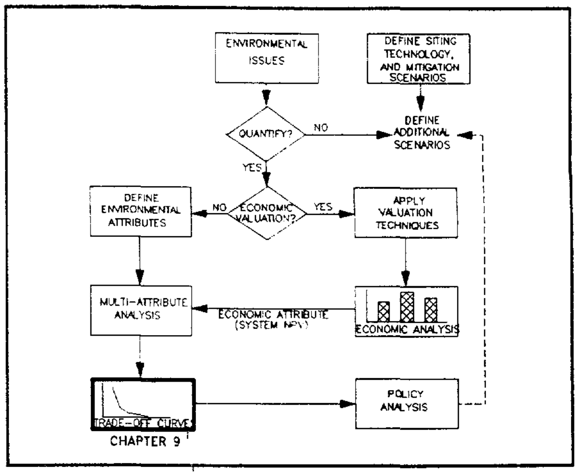
[16] Whatever may have been the licensing difficulties at this nuclear power plant, the cooling system design was never an important issue.

[17] The annual cost differential calculates as follows: 900 [Mw] x 0.6 x 8,760 [hours/year] x 1,000 [kw/mw] x 2,500 [Kcal/kwh] x 1.20 [$/million kcal fuel penalty] / 1,000,000 Kcal/million Kcal =$13million/year. The fuel cost differential is taken from the 1991 CEB Generation planning report (p.45); Mawella fuel costs are estimated at 755 cents/million Kcal, Trincomalee at 635 cents/million Kcal.

[18] A number of sewage treatment plant outfalls on the Pacific Coast of the U.S. reach depths of 50-60 meters over similar distances. For example the San Diego ocean outfall, consisting of 108-inch diameter reinforced concrete pipe, is 11,300ft long, discharging at 200ft of depth. The first 2,800ft was placed from a temporary steel trestle, the remainder from a jacking barge. The first 2,800 feet was covered with a concrete blanket to protect it against surface currents.

[19] According to the analysis conducted by the GTZ Masterplan, total employment at existing hydro plants in 1998 was 988 individuals. The largest single categories were 260 security guards, 121 unskilled laborers, 101 semi-skilled laborers, and 80 switchboard operators, and 93 other casual and unskilled jobs; these five categories therefore comprise 66% of the total.

[20] In the case of DSM measures, this is adjusted to reflect greater end-use efficiencies.



9. RESULTS

We now turn to a presentation of the results of the multi-attribute analysis. We begin with a presentation of the trade-off curves, taking one environmental attribute at a time and comparing it to the economic objective. The candidate list is then derived on the basis of the full multidimensional definitions of the selection criteria. Later we also examine strategies that combine one or more options together.

On Table 9.1 is shown the list of policies and expansion options examined, together with the abbreviated code that is used to identify points on the trade-off curves.

Table 9.1: Policies and expansion options examined

policy	abbreviation used in trade-off curves
basecase, including fluorescent lighting as illustrative DSM measure (see text)	basecase (+DSM)
no DSM (corresponds to CEB basecase)	no DSM
wind plants on South Coast	+wind
T&D loss reduction target changed from 12% to 11 %.	T&D>11
all hydro plants excluded from basecase	no hydro
no coal plants; replaced by diesels and hydro (as per CEB "no coal" option	no coal
Mawella coal (2 x 150Mw) is replaced by diesels.	Mawella>D
Trincomalee built as PFBC-combined cycle plant	PFBC
Upper Kotmale hydro plant is forced into the generation plan by 2001 (as per the CEB scenario)	Uk
The high dam/TAMS variant of the Kukule project, forced into the solution in 1999.	KukHD
The Kukule run of river variant is forced into the solution by 1999.	Ku
Trincomalee and Mawella fitted with FGD systems.	FGD
Uma Oya hydro plant built by 2001	+UO2001
Upper Kotmale hydro plant built by 2001	+UK2001
diesels use imported 1% sulfur residual oil	iresid
coal plants low sulfur (0.5%) coal	low S coal

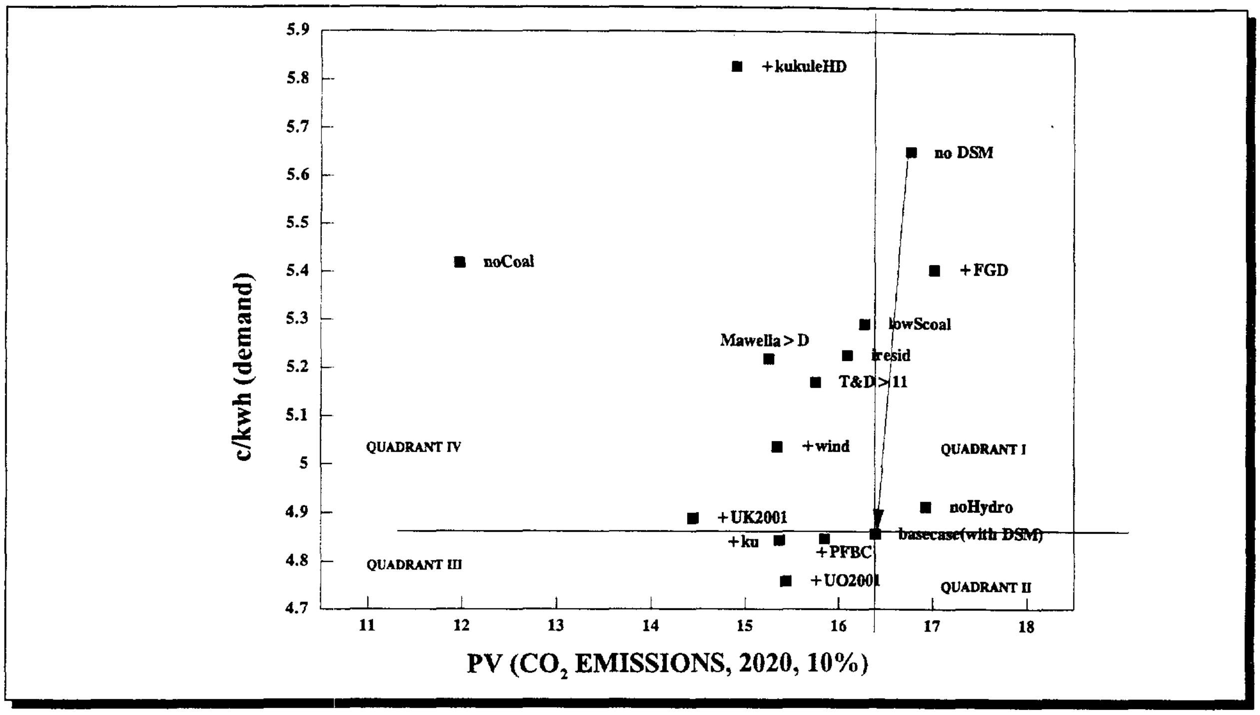


Figure 9.1: The dominance of demand side management

Demand side management

Some preliminary runs indicated that when policies were examined one at a time, DSM occurred in every non-inferior and knee set, and lay in the third quadrant with respect to the basecase in every case (see Figure 9.1). That this should be so is hardly surprising, because, in general, one would expect that improving the efficiency of end-use results in across the board reductions in emissions, and that the costs of the DSM devices (in our case the incremental cost of a compact fluorescent over an incandescent bulb) are less than the savings that result from generation savings.

It is of course conceivable that because DSM has the effect of making it possible to defer capacity additions, that it is a hydro capacity addition that may get deferred; and that in turn fossil plants may be run in those years at a level higher than if the hydro plant had been built earlier -- with the result that emissions in these years are *higher* than they would have been if the hydro plant had been built earlier. In the case of Sri Lanka, for example, if DSM permits, say, the Broadlands hydro plant to be delayed for several years, then emissions from Sapugaskanda and Kelanitissa -- both thermal plants located in the Colombo metropolitan area -- may be higher in those years. However, DSM also has the effect of reducing energy demand, which tends to offset this effect.

Figure 9.2 illustrates the impact of DSM on SO_2 emissions. In the early years until 2000, the reduction in SO_2 emissions is substantial. However, beyond 2001, because Broadlands and Ging Ganga are deferred, emissions are indeed higher (as the existing thermal plants operate more hours per year). In fact, over the entire planning horizon, the net present value of SO_2 emissions is 2.5% lower for DSM (but 6% lower for NOx, and 4.4% lower for CO_2 emissions). These, to be sure, are modest reductions, a consequence of the fact that fluorescent lighting, while having a big impact on the evening peak demand, has a relatively small impact in terms of energy. Nevertheless, to the extent that these savings occur in plants in relatively highly populated areas, the actual environmental benefit is proportionately higher. Other DSM measures may well have higher energy impacts (and hence result in larger reductions in emissions).

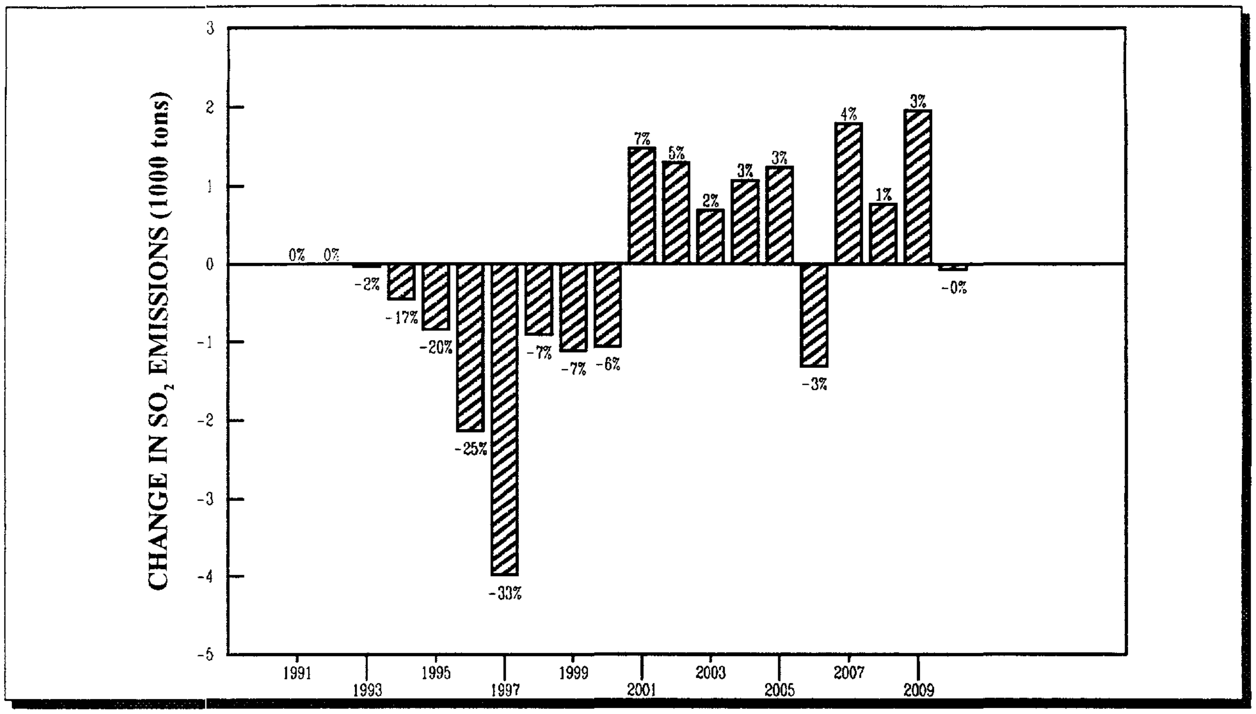


Figure 9.2: The impact of DSM on SO_2 emissions

Given the conclusion that, in light of its economic and environmental advantages, DSM ought to be part of all policy packages for the development of the power sector,[1] we therefore redefined the basecase as including DSM: that is, as we examined combinations of programs and policies, DSM was always a component of the combined strategy. Thus, for example, what is identified on Figure 9.1 as "no coal", not only replaces coal plants by a mix of diesels and hydro, it also includes DSM. The CEB original basecase, which does not include DSM, is thus the only case without DSM, and identified as "no DSM".

These results, however, need to be tempered with several cautions. First, the assumptions made about the impact of lighting load reductions on the load curve are no more than informed judgements -- in fact we use the GTZ estimate, which were also not based on actual monitoring results, or real end-use device data). Absent confirmatory evidence from real data, it would be imprudent to embark on a compact fluorescent program.

Second, we have not examined the implementation issues and the equity impacts, and the costs assumed here are only those associated with the actual devices (namely the incremental costs between fluorescents and incandescents). Experience elsewhere indicates there are substantial program implementation costs incurred by the utility as well: typically extensive information campaigns must be conducted, even if the utility were to give consumers the compact fluorescents free of charge. The assumptions made about penetration may also be quite optimistic, and would in practice be dependent upon substantial information campaign expenditures by the CEB.

Finally, as evidenced by the now quite extensive literature in the US, all manner of equity issues arise when utilities provide subsidies (as would be the case in the case of free distribution of fluorescent lights) to particular user groups. Clearly if the impact is significant in terms of energy consumption and the expansion plan, then there will also be an impact on rates.[2]

In sum, while we can conclude that the use compact fluorescents appears to be both economically and environmentally attractive, further work is needed before one embarks implementing this option. First, the model needs to be extended to incorporate the electricity

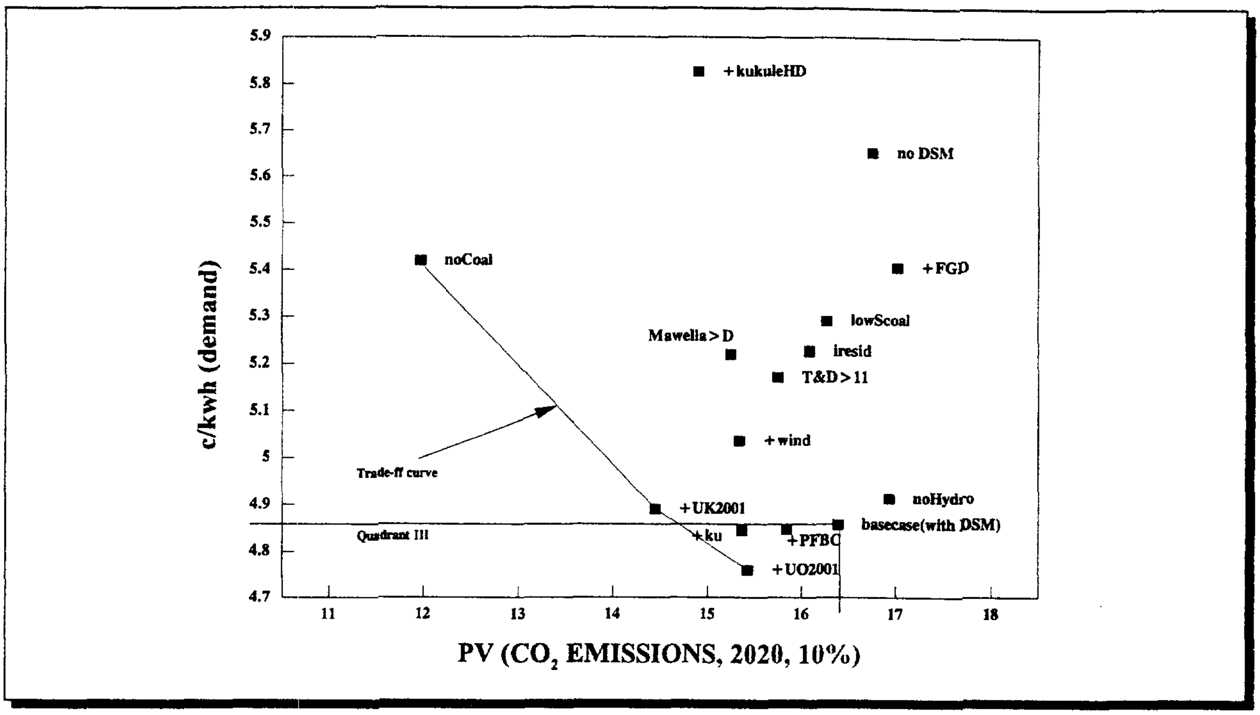


Figure 9.3: Greenhouse gas emissions

tariff impacts and the associated utility expenditures: experience in the United States shows that rate feedback effects may be quite important.[3] Second, actual Sri Lanka data is required to confirm the assumed patterns of lighting use during the evening load peak.

Greenhouse gas emissions

On Figure 9.3 we show the trade-off curve for CO_2 emissions against AIC. As one might expect, the trade-off curve includes the acceleration and addition of hydro plants (Upper Kotmale and Uma Oya), and the elimination of coal from the expansion plan (in which a combination of hydro and diesels replace Mawella and Trincomalee). The other options in quadrant III include the Kukule run-of-river project, and PFBC.

If the knee set is defined on the basis of symmetrical and equal tolerances of plus or minus 5%, then it contains the options on the non-inferior set plus Kukule run-of-river. Here is an example of where there is no pronounced knee-set, typical of situations where the non-inferior curve shows no marked change in gradient.

If the reduction in other environmental impacts is valued at zero (recall the discussion of Chapter 5), then a comparison of plans in quadrant IV -- where improvements in the environmental objective imply a worsening of the cost objective -- indicate the following results for the cost per ton of carbon emissions avoided (relative to the base case which assumes no wind power, and the Upper Kotmale project in 2008)[4]

Upper Kotmale in 2001	\$6/ton C
No Coal	\$35/ton C
Wind	\$159/ton C

The discount rate assumed for the carbon emissions is critical. The above figures assume that both the cost attribute and carbon emissions are discounted at 10%. But if carbon emissions are undiscounted, then the cost per ton avoided falls to less than 50%: for example, the cost for wind falls to \$67/ton of carbon avoided, and no coal falls to \$16/ton. This result follows immediately from the fact that while the bulk of the incremental cost is incurred in the early years (particularly for wind, with high up-front

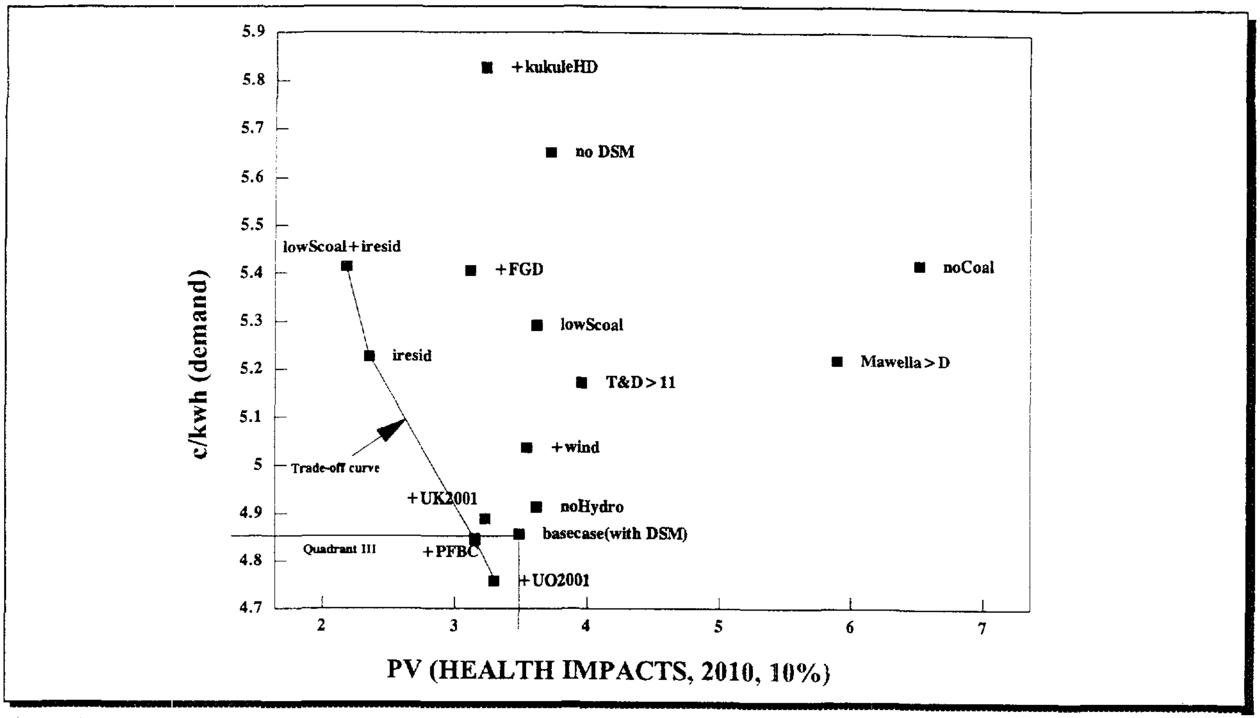


Figure 9.4: The health impact trade-off curve

capital costs), the emissions savings are spread over the lifetime of the plant.

Health impacts

The health impacts trade-off curve is illustrated on Figure 9.4. The non-inferior curve is defined by the low sulfur fuel options, PFBC, and again by an increased use of hydro.

There are two particularly instructive findings here. First is that the no coal option, and the replacement of Mawella by diesels, worsens the health impacts unless accompanied by the use of low sulfur fuels. This is simply a consequence of the likely locations of the diesels that would replace the coal plants: located in or close to urban areas, and therefore in much greater proximity to population, the associated health impact will obviously be larger than that of coal plants located far from the population centers.

The second relates to the effectiveness of FGD, which is neither in the non-inferior set, nor in the knee set. On the other hand, PFBC is in the knee set (and also lies in quadrant III). When one also takes into account the CO_2 emissions trade-off curve, for which FGD is in quadrant I (i.e. worse than the basecase in both cost and CO_2 emissions), the superiority of PFBC (and possibly other of the newer clean coal technologies not examined here) becomes evident.

Indeed, a comparison of the health impact and SO_2 reduction trade-off curves is quite instructive: if one looks only at emissions, it comes as little surprise that FGD does now lie on the trade-off curve (Figure 9.5). However, the low sulfur fuel option is not significantly dominated, and is included in the knee set for these attributes. The point here is that strategies that may appear effective from the standpoint of reducing emissions may or may not be effective to reduce impacts in a cost-effective way.

These results are of course a function of the assumption made for the sulfur content of domestically produced residual oil, whose specification for sulfur is no more than 3.5% by weight. Because the refinery at Sapugaskanda has been running low sulfur crudes over the last few years, actual sulfur contents are considerably lower than this: in this case study we have assumed 2.5%. Unfortunately no reliable data are available on the sulfur content of the residual oil actually produced at

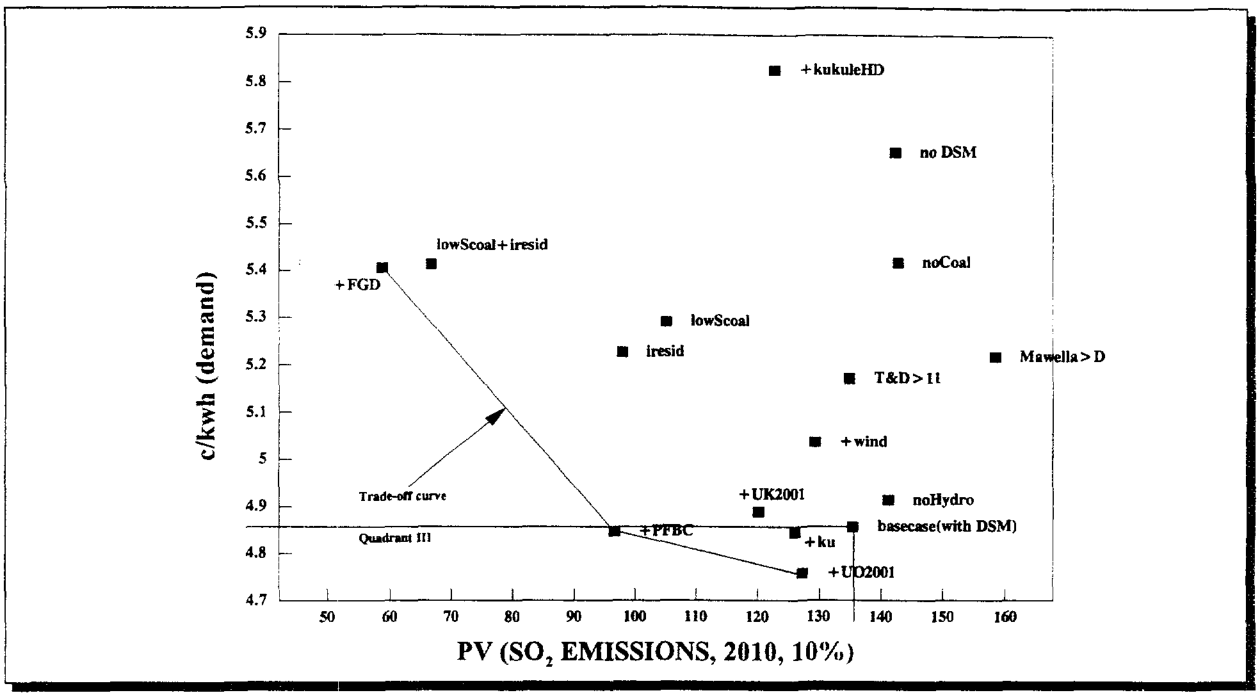


Figure 9.5: The trade-off curve for SO_2 emissions

Sapugaskanda. Clearly this is an area where better data needs to be developed before definitive conclusions are derived.[5]

Acid rain precursor emissions

The non-inferior curve for acid rain precursors (Figure 9.6) is not much different to that for SO_2 emissions. PFBC retains its advantage when NOx emissions are also considered, given its ability to reduce NOx emissions as well.

Table 9.2: Impact of the discount rate: NPV

case	10%	12%
basecase (with DSM)	1688	1422
+upper kotmale	1699	1448
no coal	1883	1477
no DSM	1965	1633
+Kukule (high dam variant)	2025	1745

Impact of the discount rate

Although the discount rate is not a policy variable, it is important to understand the role of the discount rate on the results (see Table 9.1), particularly for those options that differ materially in their capital intensity. The rankings remain unchanged.

However, the real question from our standpoint concerns not the economic criterion alone, but the trade-off curves. As discussed previously, we have not used a different discount rate for the environmental impacts; thus a higher discount rate applied to economic costs also means that a higher discount rate is used for the environmental impacts.

On Figure 9.7 we show the trade-off curve for health effects using a 12% discount rate (which should be compared to the earlier trade-off curve for 10% discount rate shown on Figure 9.4) Although the shape of the trade-off curve is somewhat different, the plans in the non-inferior set remain largely unchanged. Capital intensive options (hydro, and PFBC) are further to the right, as expected. Thus the Kukule run-of-river project, which was in Quadrant III with respect to the basecase at a 10% discount rate, moves to the right, and is now in quadrant II at the higher discount rate.

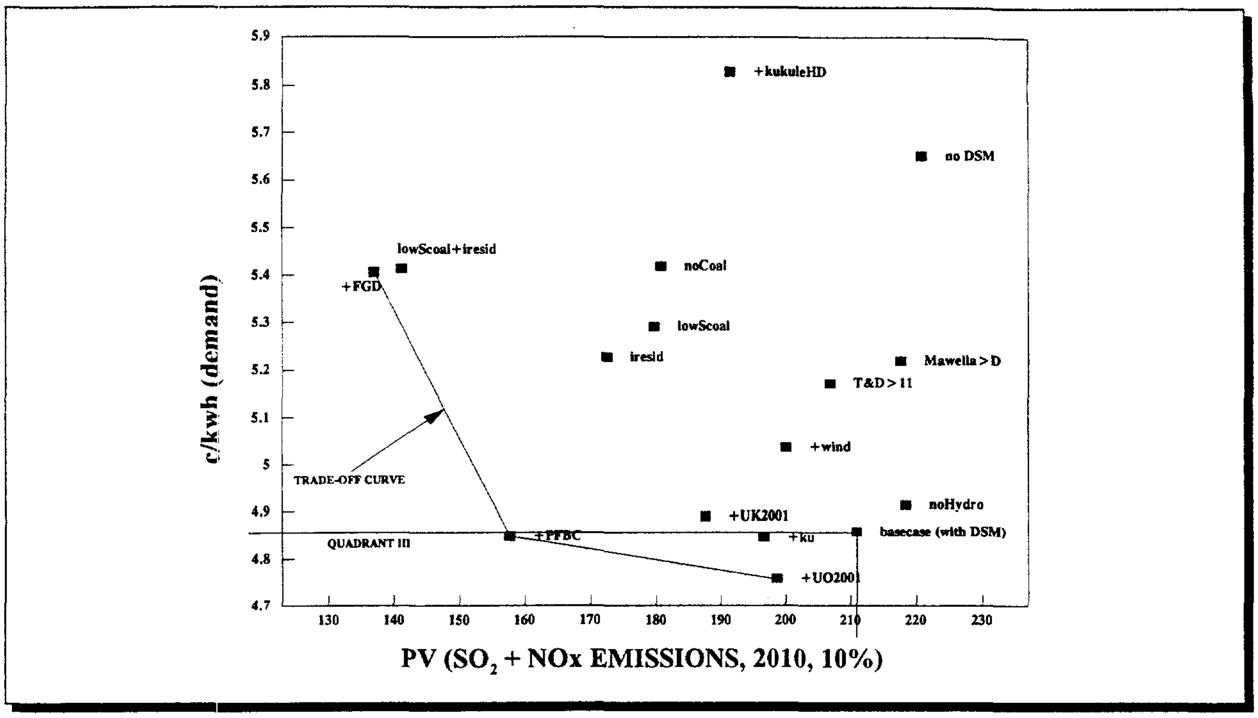


Figure 9.6: Trade-off curve for acid rain precursor emissions

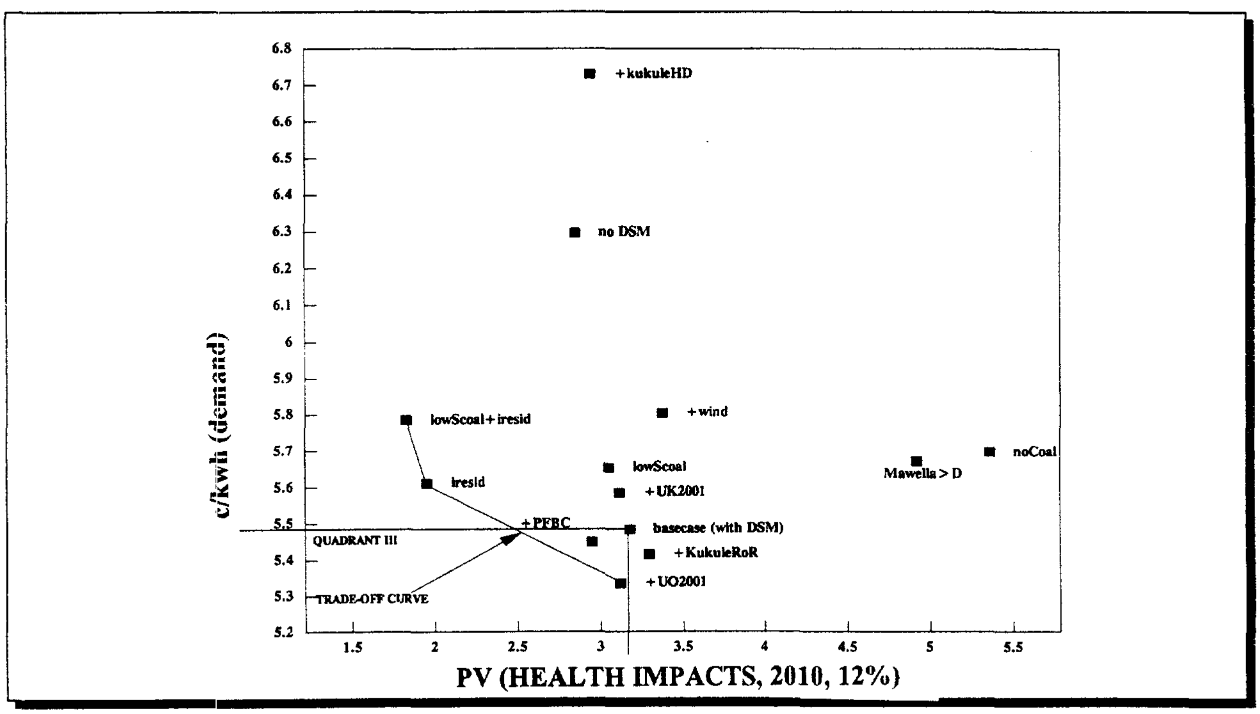


Figure 9.7: The health impact trade-off curve at 12% discount rate

The Upper Kotmale project is also relatively less attractive. However, the Uma Oya project remains in the non-inferior set.

Employment

As one might expect, the non-inferior curve for employment (Figure 9.8) is defined by the large hydro projects that require a relatively large local construction workforce. Note that since employment generation is a benefit from the national perspective, the non-inferior curve curves to the right, rather than to the left as in the previously presented cases of costs.[6]

We have assumed no incremental employment effect for DSM; however, it might be noted that a number of studies in the industrialized countries indicate that the number of new jobs created by energy efficiency projects is greater than the number generated by an equivalent supply-side project.[7]

The direct externalities of hydro plants.

There are certain environmental externalities for which valuation is relatively easy. At hydro plants the costs of resettlement, and the opportunity costs of lost production, are readily calculated: indeed this was done by the GTZ masterplan study. However, to date these secondary costs have not been included in the capital costs used in the CEB generation planning studies.

The importance of these secondary costs varies considerably among hydro plants; the effect is illustrated on Figure 9.9, in which the impact of these costs on the employment benefit trade-off curve is depicted. Obviously the result is a downward shift in the curve if the secondary costs are excluded. However, for the projects indicated, only in the case of the Kukule high dam variant is the change significant.

Biodiversity

The biodiversity impact trade-off analysis is depicted on Figure 9.10. The non-inferior point obviously has as one of its endpoints a no hydro option (in which Broadlands, Ging Ganga and Uma Oya are all forced out of the base case): the assumption here is that all of the thermal projects that would replace the hydro plants would be at sites of poor biodiversity value close to load centers. Certainly the high dam variant of Kukule implies a potential loss to biodiversity value (B=530) that is eight times

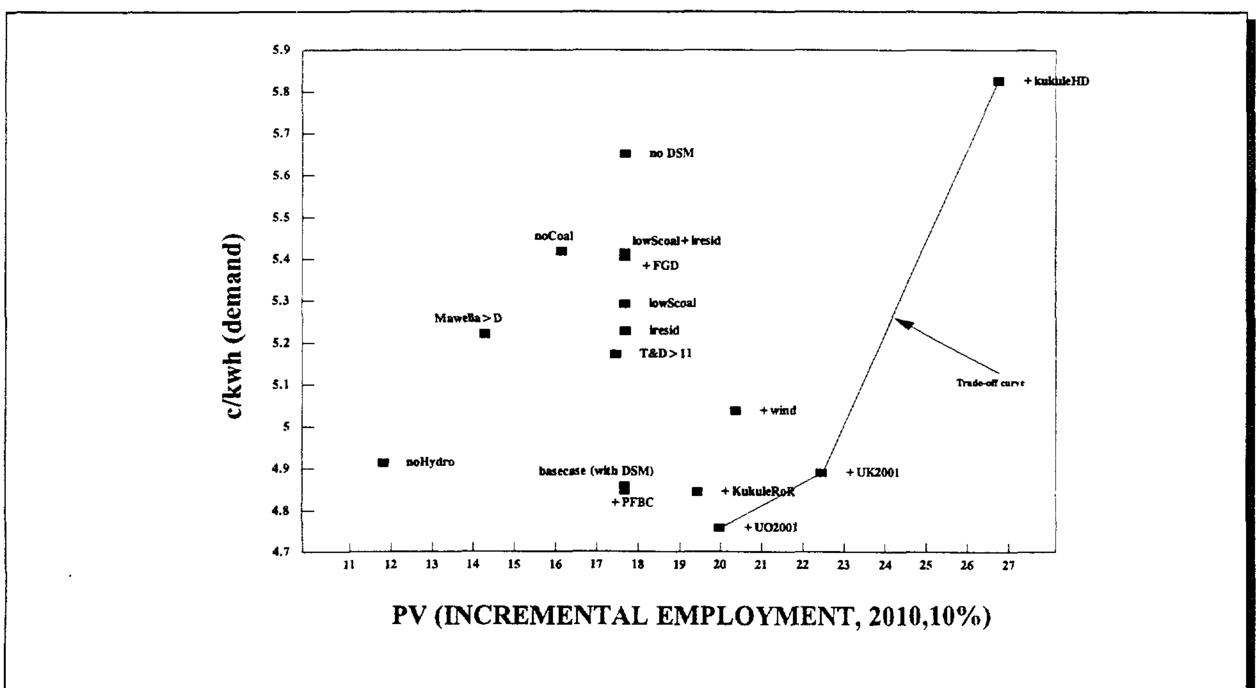


Figure 9.8: The trade-off curve for employment impacts

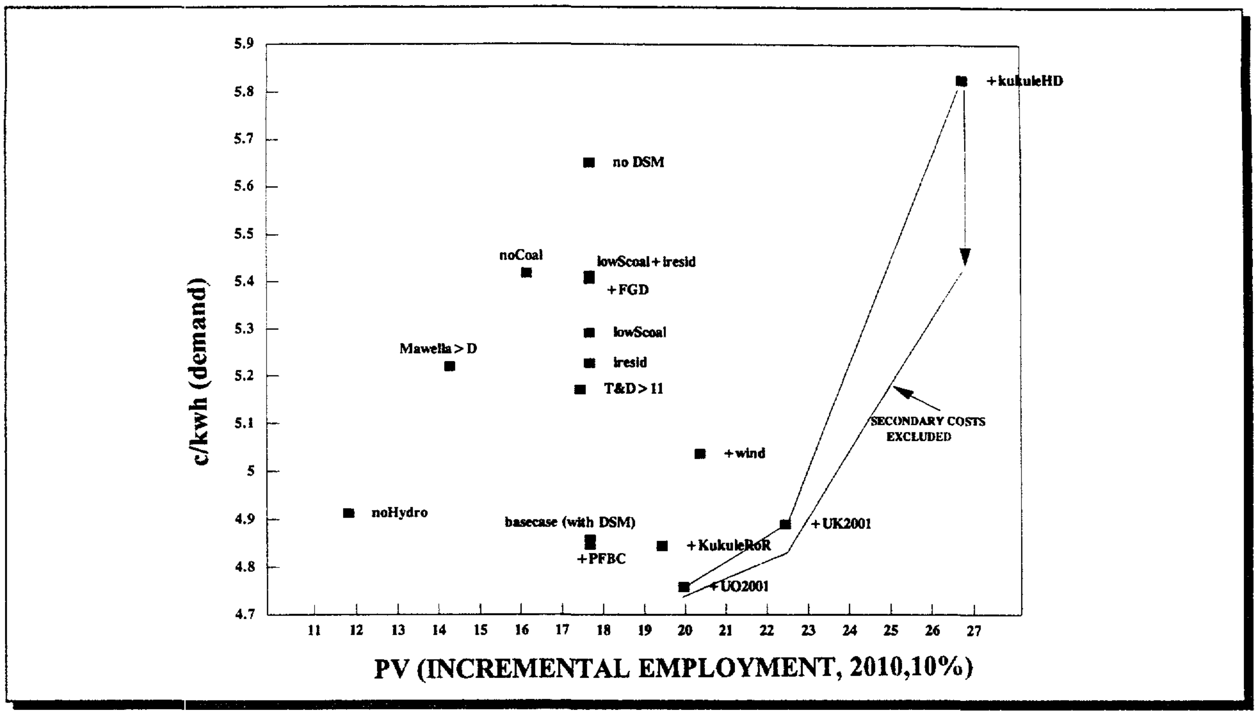


Figure 9.9: The impact of including the direct externality costs of hydro plants

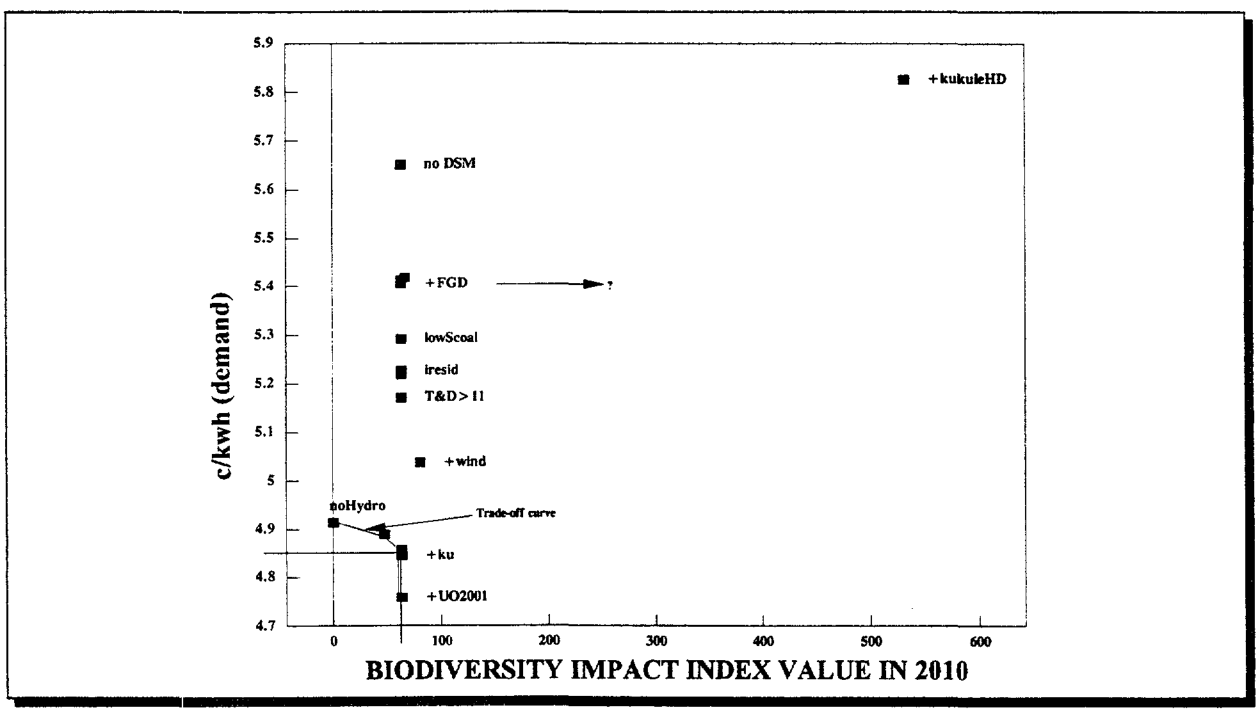


Figure 9.10: Biodiversity index trade-off curve

that of the majority of the policy options (B=50 to 70).

Although the wind plants would require a rather large land area, the vegetation of the area on the south coast has rather low biodiversity value, and therefore the overall increase in biodiversity impact of this option is judged small.

Thermal Plume Impacts

As noted in Chapter 8, quantification of the trade-offs related to the impacts of thermal plumes on aquatic ecosystems requires a somewhat different approach to that presented above for the other major attributes. Moreover, because of resource constraints, we have not been able to conduct the sort of thermal plume modelling and engineering cost estimation of mitigation options that would be required to provide a more definitive analysis. Consequently, what is possible here is only to sketch the outlines of the analysis that should be conducted once this information does become available. On Table 9.3 we compare the differential site costs, as indicated in the Trincomalee EIS. The item for "circulating water" includes a capitalization of the operating cost differential associated with different pumping heads at the different sites. The total costs of site 3A-2 are seen to be only marginally higher than that of the BVI recommended site 2A-2. As already noted in a previous chapter, BVI's incorporation of "environmental factors" into the site ranking process seems somewhat unreliable: it is certainly true that no thermal modelling results are presented for site 3A-2. Because this site is nearer to the deeper waters of Koddiyar Bay, and because aquatic ecosystem effects are demonstrably the most important environmental impact to be considered, we consider this site to be potentially attractive.

With thermal plume modelling studies in hand for both these sites and for a variety of cooling system configurations, and for comparable representative locations on the south coast, Table 9.3 could be expanded on the cost side, and a trade-off curve of the type illustrated on Figure 8.8 could be drawn. For the moment we have only one point on this curve: from the modeling studies for once-through cooling at site 2A (see Figure 9.11) the area of the thermal plume with a 1°C rise above ambient, located in well-mixed shallow waters, is 160ha (for the full 900Mw development at the site).

The candidate list

Although the discussion here has thus far been focussed on the two-dimensional trade-off curves, as noted in Chapter 5, examination of the two-dimensional plots alone is insufficient to establish the complete trade-off surface. Only the application of the set definition rules in the n-dimensional attribute space provides a rigorous definition. On Table 9.4 we summarize the set of plans and policies that emerge by application of each criterion: a discussion of the policy implications is presented in the next Chapter.

Table 9.3: Differential site costs

	1	2A-2	3A-2	4
transmission	5790	2670	70	0
coal handling	0	3270	1630	3840
circulating water	41830	0	10440	14390
site clearing	16380	9940	0	23190
foundations	0	0	0	0
ash disposal	6010	8170	11950	0
transportation	3120	0	0	3460
total	73100	24050	24090	44880

Table 9.4: Candidate lists

Quadrant test [a]	non-inferior set	knee set
{DSM}[b]	{DSM}[b]	{DSM}[b]
	{no coal}	{no coal}
{PFBC}	{PFBC}	{PFBC}
{Uma Oya}	{Uma Oya}	{Uma Oya}
	{imported resid}	{imported resid}
	{low S coal+ imported resid}	{low S coal+ imported resid}
	{FGD}	{FGD}
	{Upper Kotmale}	{Upper Kotmale}
{kukule RoR}		
		{Mawella>D}
		{T&D losses>11%}
	{no hydro}	
	{kukule HD}	

[a] This is the multidimensional equivalent of the two-dimensional "Quadrant III" criterion: these are plans that are better than the basecase in at least one attribute, and no worse in any others.
[b] DSM is included in the basecase, as discussed in the preceding text.

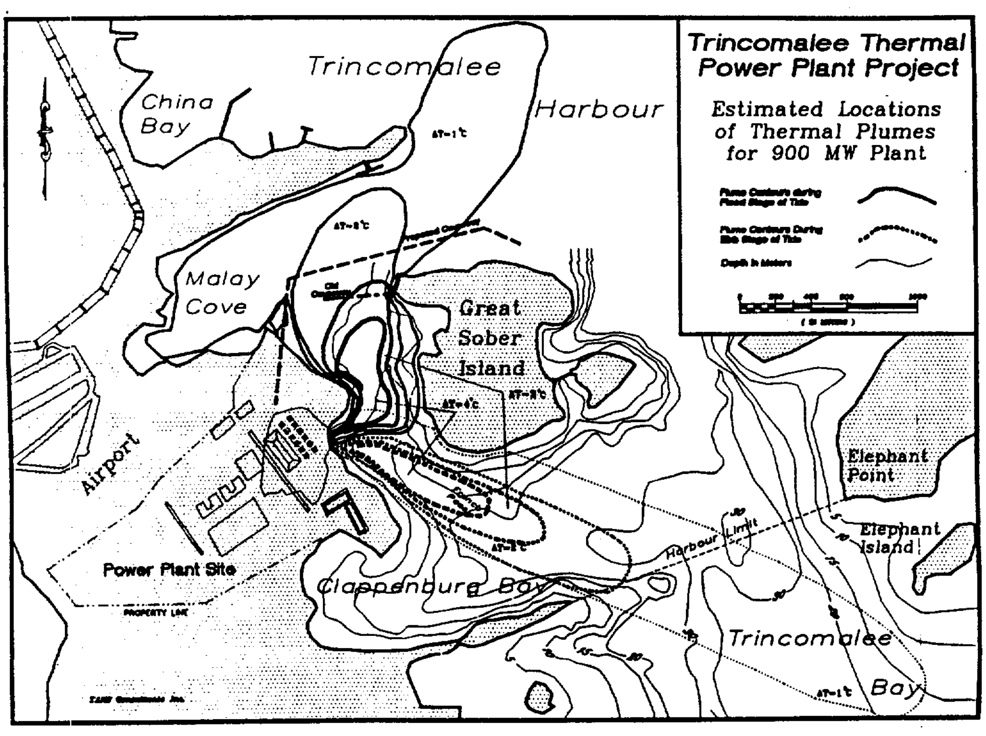


Figure 9.11: Thermal plumes at site 2A (from the EIS, Figure 8.4)

Notes

[1] Just such a recommendation was adopted by the report of the Official Committee to study Sri Lanka's power needs, appointed by the Cabinet Subcommittee on Foreign Investments in April 1992. Recommendation (3) urges a number of DSM measures for immediate (including high-efficiency lighting) and medium term implementation.

[2] Two recent articles illustrate the controversy over the experience with DSM programs in the US, where DSM now accounts for about 25% of expenditures for supply side expansion. P. Joskow and D. Marron, What does a negawatt really cost? Evidence from utility conservation programs, Energy Journal, 13, 4, 1992, pp. 41-74, suggests that the cost to utilities of implementing DSM programs is substantially higher than is often presumed. E. Hirst, Price and cost impacts of utility DSM programs, Energy Journal, 13, 4, 1992, p.75, argues that while DSM may raise electricity prices, the increase is less than the decrease in costs.

[3] If DSM results in lower rates (a possibility in the short run if investments can be deferred), or if consumers have lower electricity bills as a result of the device savings, then there may be less incentive to conserve: lights in empty rooms may not get switched off as they otherwise might do so.

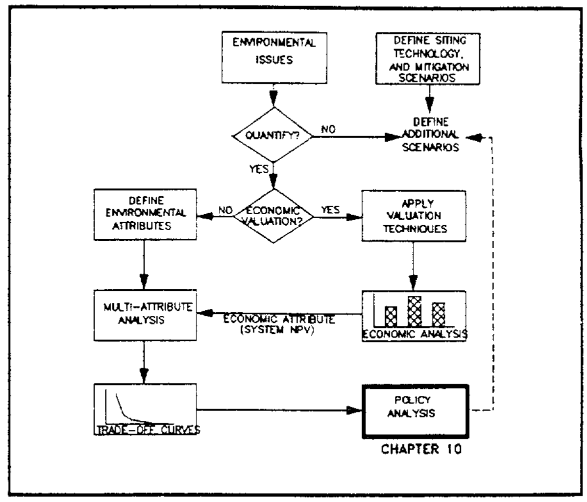
[4] It should be noted that these costs represent the change in *supply* cost if the options in question are forced into the plan. There may also be an additional social cost associated with the loss of consumer surplus if increases in supply cost lead to increases in tariff. The impact of such price effects is discussed further in Meier, Munasinghe and Siyambalapitiya (1993).

[5] Another issue is the degree to which there is an adequate supply of high sulfur oil available from the Sapugaskanda refinery: at the moment this is in excess, but towards the late 1990 it is expected that domestic demands will utilize all residual production. Consequently, heavy fueloil would need to be imported for those options which require extensive use of diesels.

[6] Whether this is also true from the local perspective is a matter for the project level environmental assessment. Clearly large construction projects in relatively remote sites may strain the ability of local communities to handle the influx of temporary workers.

[7] See e.g. Council on Economic Priorities, *Jobs and Energy: The employment and economic impacts of nuclear power, conservation and other energy options*, New York, 1979. This study, which examined energy options for Long Island, concluded that a conservation strategy generated more than twice the regional employment than what would be required by an equivalent supply side strategy; the national employment effect was estimated at 1.5 times higher for the conservation strategy. As in Sri Lanka, Long Island has no heavy electrical equipment manufacturing industry, so the bulk of the equipment associated with supply side generation projects need to be imported (in the case of Long Island, from other areas of the United States).

10. POLICY IMPLICATIONS



We conclude this report with a discussion of the policy issues and conclusions raised by the analysis presented in the previous chapters. This is divided into three parts. First, a discussion of procedural issues (how should current planning procedures be modified to better incorporate environmental considerations. Second, a discussion of important environmental policy issues (such as the criteria for setting standards). Third, a discussion of technology choice issues. Finally we present recommendations for further applied research that address some of the limitations of this initial study.

Procedural Issues

CEB Planning Procedures: At present the CEB does not include the costs of resettlement or the opportunity costs of lost production at hydro plants in its generation planning studies. For some major hydro projects, this clearly a significant issue, increasing capital investment by as much as 10% (although at many others, such as at Broadlands, there are no resettlement costs). While one can reasonably argue against the inclusion of opportunity costs in investment decisions, resettlement costs represent unambiguous incremental cash outlays during the construction phase, and need to be included. In any event, since, for example, the costs of NO_x control are added to the capital costs of diesel plants, exclusion of direct mitigation costs for hydro plants is illogical.

The ability of the WASP-III model to deal with the generation planning options in Sri Lanka is subject to some serious question. Not only are the shortcomings of the model with respect to hydro treatment fairly well recognized, but this study has raised a number of issues concerning the robustness of the so-called "optimal" solutions.

Peer review: The CEB has instituted a system of independent technical peer review, as was most recently done for the Kukule hydro feasibility studies: independent experts with no vested interest in the outcome of the analysis were brought in to review various aspects of engineering design, civil works, engineering geology, and so on.[1]

Such a system ought to be instituted for environmental studies as well. Independent experts with no association with the contractor ought to serve in a review and advisory capacity. For thermal plants, for which there is clearly no in-country experience in dealing with air and thermal pollution issues, international experts ought to be available to CEB as independent reviewers. While this may be expensive, it represents a very small fraction of the costs associated with delays that inevitably follow public controversies over the adequacy of environmental studies. For thermal plants, then, the review group should include an expert in air quality modeling and related risk assessment issues, an expert in thermal plume modeling, and an expert in aquatic ecosystems. In the case of hydro plants, the team should include a social scientist (to provide guidance on resettlement and relocation design), a biologist, and an environmental economist.

Environmental studies: It should be noted that CEB has already taken the first steps in

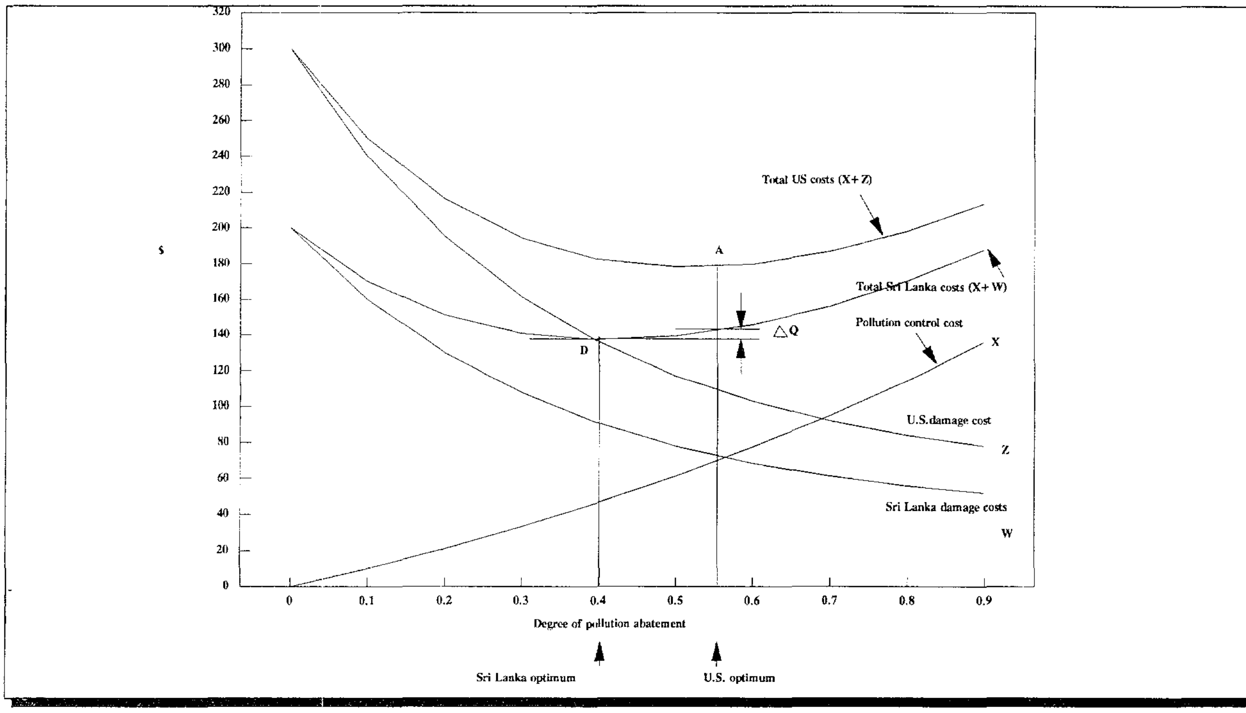


Figure 10.1: Damage functions and environmental standards.

analyzing environmental concerns in its planning studies, and the 1992 generation plan is the first to include some discussion and analysis of environmental issues. Both ENVIROPLAN and the air quality model are being used by the generation planning branch, and will provide a nucleus of trained staff and analytical capability for the proposed environmental cell that is required for by the National Environmental Action Plan.[2] However, this cell ought not merely to be reactive in nature, responding to day-to-day issues, but ought to play a proactive role by maintaining an on-going program of environmental analysis that is relevant to the long term needs of CEB.

The most urgent priority for such long term environmental study is in the area of thermal plume modeling. The sort of detailed analysis provided in the BVI EIS for Trincomalee, for once-through cooling at the Clappenburg Bay-French Pass site (SITE 2A), needs to be extended, at a minimum, to SITE 3A on Koddiyar Bay, and to one or two representative sites on the south coast. The modeling should be done not just for once-through cooling, but for a range of options to include ocean outfalls, with and without diffuser systems, and for cooling towers. Cost estimates for the various options should also be developed. Only with this information in hand can the trade-offs across the various siting options for coal plants be realistically assessed.

Policy Issues

Health based standards: whatever may be the difficulties of explicit valuation of environmental externalities, the effort ought still to be made provided one is mindful of the assumptions and limitations. While the argument that in the absence of damage valuation studies one ought simply to be conservative has a certain political appeal, adopting the environmental and ambient standards of the industrialized countries may imply a serious misallocation of resources.

Suppose for the moment that the standard for the United States is properly defined at (or near) A, based on the American damage curve Z -- as illustrated on Figure 10.1. Assume further that the cost function for pollution abatement, say X, is the same in both the United States and Sri Lanka -- a reasonable assumption for FGD systems equipment, for example. But suppose the damage curve in Sri Lanka is W, which implies an optimum at D, not A. Since a large part of the total environmental damage relates to the costs of health care and societal valuations of morbidity and mortality, there seems little question that this damage function does indeed lie below that incurred the United States. It follows that use of the American standard implies an over-investment in pollution control by the amount ΔQ.

Perhaps the most important point is that even if it is true that environmental standards are not strictly optimal in economic terms, at least in the industrialized countries there are institutional mechanisms that ensure extensive and informed public discussions of proposed regulations; the Environmental Protection Agency, for example, is required to conduct a detailed economic impact analysis of proposed emission standards on the affected industries. Such a debate is still almost entirely absent in most developing countries, and the resource allocation decisions implied by the adoption of standards, or "environmental guidelines", ought almost certainly not be made by well-meaning functionaries at the international financial institutions responding to pressures from American environmental groups.

The argument that health-based standards should be absolute -- meaning that the value of a human being is the same wherever he or she may be -- may have ethical merit, but its selective and isolated application to power sector projects is irrational. Why should the Sri Lanka government be forced to accept an implied valuation of \$1,500,000 per human life necessary to justify an FGD system, when expenditures on road safety, anti-smoking, and basic health care imply human life valuations one if not two orders of magnitude less. Expressed differently, if the Sri Lanka government can justify increased expenditures on human health care, these resources should be applied where they have maximum benefit. The reality in most developing countries is that there are many more pressing public health problems than respiratory diseases induced by incremental ambient concentrations of sulfates and fine particulates caused by power plants.

In any event, the fact that some aspects of the environmental debate in the United States have long been irrational from the standpoint of benefit cost analysis means that one needs to examine very carefully the potential applicability and effectiveness of American strategies to developing countries. Only very recently has it become recognized in the United States that the risks to human health from indoor pollution, whether from smoking or gas cooking, far exceed those from power sector induced particulate emissions, to say nothing of the irrationality of continued subsidies to tobacco farmers while imposing ever tighter emission requirements on new power plants. Moreover, the failure of the traditional reliance on a command-and-control approach to environmental policy has been tacitly recognized by the recent amendments to the Clean Air Act, which will introduce a system of tradable emission rights that will have the effect of letting utilities and the marketplace decide what constitutes the most cost effective way of compliance.[3]

Tall stacks: Tall stacks are expressly excluded as means of assuring compliance with ambient air quality standards in the United States. This was a rational modification of policy, since tall stacks were used mainly at large mine mouth power plants in the central United States; the prevailing weather patterns with westerly winds for most of the year meant that long-range transport aggravated air quality problems in the northeastern United States and Canada.

The view that since tall stacks are inappropriate for the United States and Europe, they should also be disallowed in developing countries as a compliance device is quite widely held. While we certainly are not advocating tall stacks as a compliance mechanism, it would seem that the option ought not to be dismissed without a careful case by case examination for tropical islands, given the very high costs of alternative means of SO_2 reduction. For example, at the Mawella location, the distribution of prevailing winds is strongly bimodal, corresponding to the SW and NE monsoons. Long range transport in this case disperses pollutants entirely over the ocean during the northwest monsoon, and after a short overland distance during the southeast monsoon. Consequently if in fact short range air quality standards might be violated in the vicinity of Mawella, tall stacks would be a perfectly rational solution since any long range deposition (that typically occur over distances between 200-800 kms) would occur almost entirely over the Bay of Bengal or the south Indian Ocean.

FGD systems: The results show clearly that if in fact one wishes to spend resources on SO_2 emission reductions, the importation of low sulfur fueloil for use at diesel plants costs less than one third per ton of SO_2 removed than by FGD systems. And when population-weighted health impacts are considered, the value of FGD systems in the relatively remote locations being considered for coal plants is even less, compared to fueloil sulfur removal at diesel plants located close to populated areas.

Technology choice issues

DSM: The first conclusion, which is of course entirely expected, is the attractiveness of demand side management (DSM) from both the economic and environmental standpoints. Our representative DSM measure, fluorescent lighting, enters the short list of attractive policies for all attributes examined: and we therefore redefined the base case to include DSM. A detailed study of a broader set of potential DSM opportunities in Sri Lanka ought to be given high priority.[4]

To be sure, because the peak use of lighting occurs in the early evening hours at the time of the daily system peak, it has an unusually large impact on the system peak, and hence an unusually large impact on capacity requirements. Other DSM measures would be expected to have a considerably smaller impact on capacity requirements; but may on the other hand also save larger amounts of energy.

Indeed, as indicated on Figure 10.2, our representative wind energy scenario, which foresees 155Mw of wind capacity on the South coast by 2001, will provide significantly more energy than fluorescent lighting may save: however, as noted previously, wind plants will not significantly reduce the peak capacity requirement. This also underscores the need to examine alternative options in a systems context, for comparisons of technologies in isolation of their systemic context simply cannot capture such interactions.

Several cautions need to be noted. First, we have not addressed here the implementation issues of a fluorescent lighting replacement program, which, given the experience elsewhere, are likely to be substantial, and which also raise a range of equity issues.

Second, even before specific DSM program options can be formulated, much more information is needed on the hour-by-hour composition of load by end-use device. CEB needs to begin studies to collect such information.

Coal projects: It seems fairly clear that from a cost standpoint, Trincomalee is a superior site for coal plant development to any south coast location; the specific cost comparisons derived in Chapter 5 (see Figure 5.5) indicate that Mawella has specific costs about 20% greater than Trincomalee. This conclusion remains unchanged when the cost of environmental damages is taken into account: there is no reason to assume that the environmental damages of a plant on the south coast are any smaller than those of a plant in the Trincomalee Bay area that has been properly designed to mitigate undesirable impacts of thermal effluents.

At the time this study was conducted, the operating assumption was that Mawella would be developed before Trincomalee: more recently interest in developing Trincomalee as a private power project, and opposition in the Mawella region to such a coal plant, has rekindled interest in developing Trincomalee as the first coal plant site. The only justification for developing a higher cost site before a lower cost site would be security considerations that might preclude Trincomalee from earlier development. However, the results of this study suggest that if security reasons do in fact prevent Trincomalee development before 2003 (i.e. before a construction start in 1997), then it is not clear that one would still want to develop Mawella (or some other south coast site). The critical issue

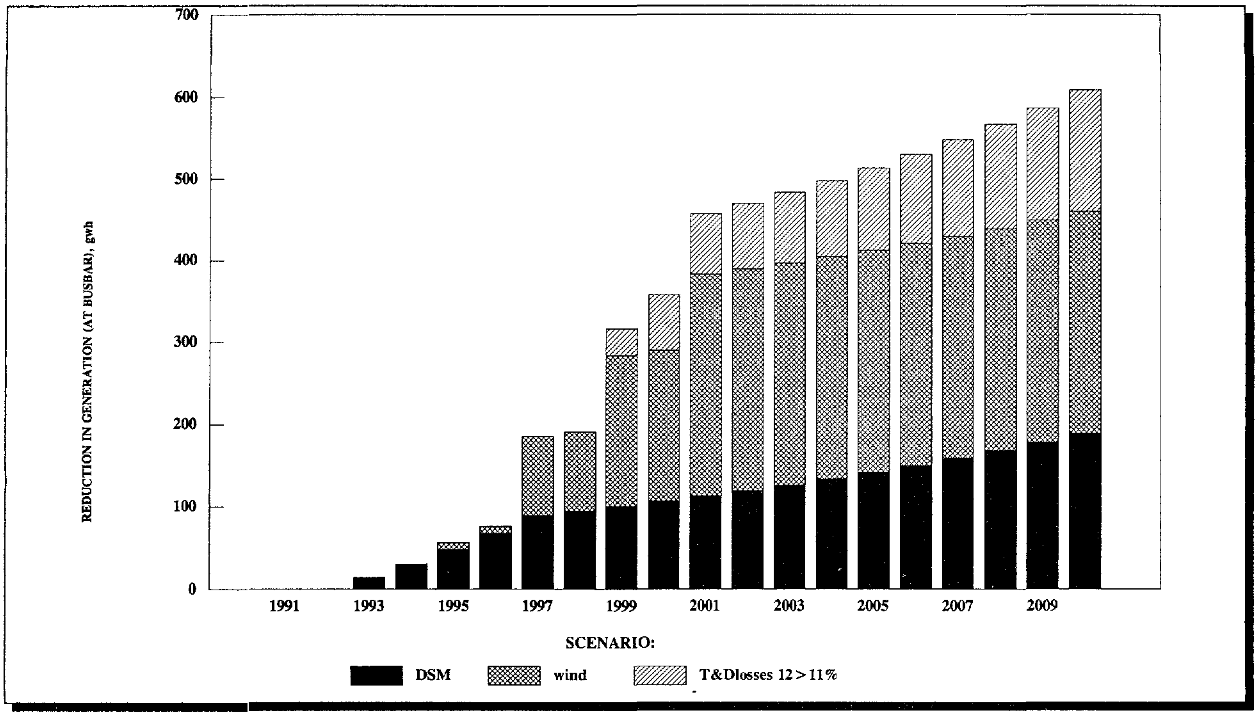


Figure 10.2: Impact of wind, DSM, and transmission loss reductions on generation requirement

here is the location and sulfur content of the fuel of the diesels that would be required to eliminate coal at Mawella.

More importantly, our analysis of the aquatic ecosystem impacts of a coal plant on Trincomalee Bay show that if the reason for denying a permit is the potential environmental risk to the aquatic resources of the Bay, there are more cost effective ways of dealing with that risk than to build the plant at Mawella. In particular, the study indicates that the additional costs of $8/ton of coal incurred at Mawella (because of the lack of a deepwater harbor that can accommodate vessels of the size possible at Trincomalee) are larger than the incremental costs of a long outfall that would discharge heated effluents at greater depth out in the Bay, rather than close to shore as envisaged by the present design. To be sure, we have not conducted a detailed feasibility study of such an option, but the evidence is sufficiently strong to warrant closer examination.

T&D loss reduction: The most important result of our analysis with respect to T&D loss reduction is its relationship to the implementation of DSM measures. Whether or not DSM is implemented, a 4-year delay in reaching the 12% target (i.e. from 1998 to 2002) increases both costs and emissions -- as illustrated on Figure 10.3 for the cost-CO_2 emission trade-off.

However, when one examines the possibility of reducing T&D losses to 11 rather than 12%, then whether or not DSM is also implemented makes a significant difference. Obviously, in both cases, CO_2 (and indeed other) emissions will decrease further. However, in the absence of DSM, the further reduction also reduces costs, whereas if DSM is also implemented, the cost increases.

This result is not unexpected: since the particular DSM measure considered in this analysis -- fluorescent lighting -- has a sharp impact on the peak demand, and since reduction of T&D losses brings a disproportionate benefit to the peak period (because losses vary with the square of the load), the two measures interact through their respective impacts on the load duration curve.

While we do not claim to have made any detailed engineering study of these issues -- and our cost estimates of bringing losses down to 11% are subject to considerable uncertainty -- nevertheless the conclusion is an important one

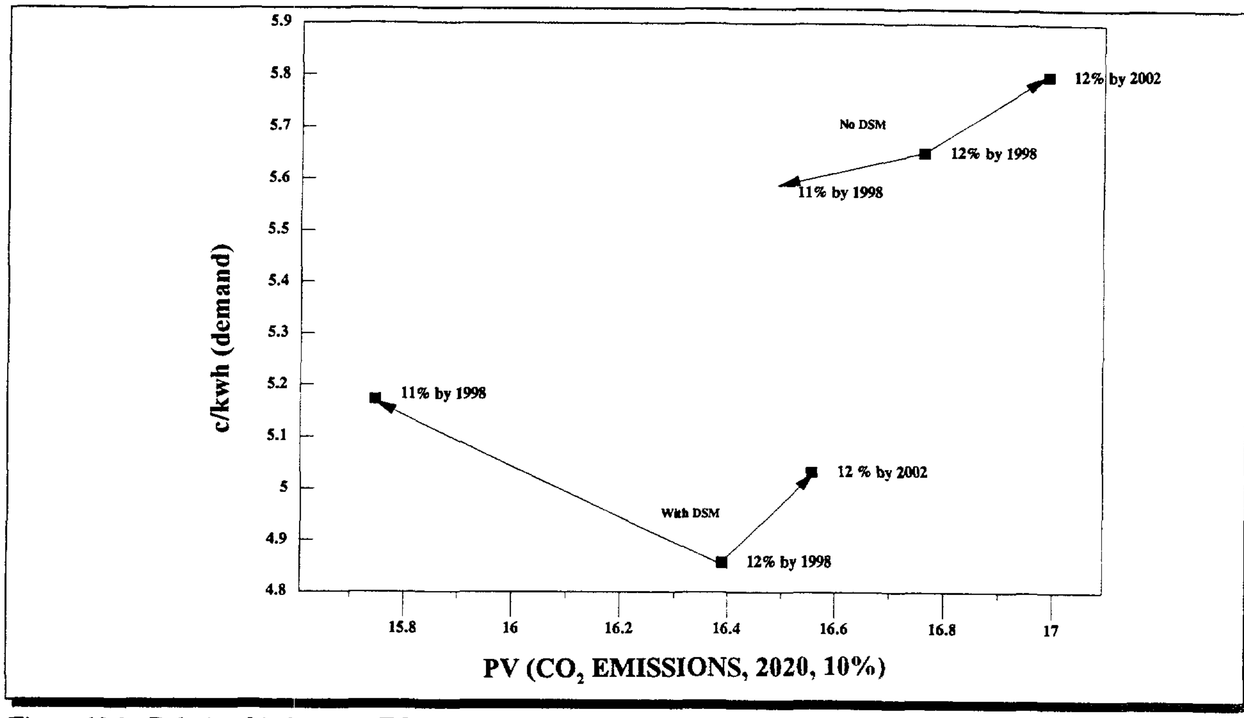


Figure 10.3: Relationship between T&D loss reduction and DSM program implementation.

because it illustrates once again the need for evaluating options in a systems context.

PFBC: Pressurized fluidized bed combustion using the combined cycle appears to be an extremely attractive technology for Sri Lanka. Even if the installed cost per Kw is comparable to that of a pulverized coal plant with FGD system, its suitability to be employed in a combined cycle means that the incremental costs (vis-a-vis a coal plant without FGD) are largely offset by coal savings that follow from improved heat rates.

In any event, since PFBC also results in substantial NO_x reductions, and because of heat rate savings lower CO_2 emissions per net kwh, from an overall environmental viewpoint PFBC-CC is much more attractive than merely fitting an FGD system to a conventional pulverized coal plant (which, all other things equal, increases CO_2 emissions per net kwh generated).

The main question, however, concerns the commercial availability. CEB should carefully monitor the progress of commercial demonstration and availability of PFBC technology. Preliminary discussions might be held with ASEA-Brown Boveri, the manufacturer of all of the important utility scale PFBC projects to date, on issues such as commercial availability, suitability to imported Australian coals, local availability and cost of sorbents, likely cost and performance.

To be sure, PFBC is a sophisticated technology, and there may well be those who question whether such a plant might be satisfactorily operated in Sri Lanka. However, the same could be said of even a conventional pulverized coal plant, which would also represent a new technology for the CEB.[5]

Further work

We view this case study as only the beginning of a long term effort to integrate environmental considerations into energy sector planning in Sri Lanka. Several extensions of the present framework will be undertaken in a second phase of the work:

1. Pricing and tax policy. In the present case study we have used exogenously specified demand projections, and tax and pricing policy options have not been studied. There is a need to expand the present model to include a financial model of CEB, so that the tariff implications of

technology and pollution mitigation choices can be assessed, and then to provide a feedback to the demand projection. This would also permit examination of tax and pricing policy options (such as carbon taxes on fossil fuels, or LRMC-based pricing) on a consistent basis with technology options.

2. The broader energy sector context. In the present case study we have not examined the consequences of electric sector policy choices on other subsectors. Some of these effects may be quite significant. For example, the choice between coal and diesels has important ramifications for refinery operations, and on the balance between importing (and refining) crude and importing petroleum products. Indeed, a number of important energy-environmental issues such as greenhouse gas (GHG) emissions reductions must of necessity be studied for the energy sector as a whole, rather than just for the electric utility alone.

A good example of the need to broaden the study to include at least the petroleum and refining sectors is the issue of low-sulfur fueloil. In this study we have simply assumed that low sulfur fueloil would be imported. However, this may not in fact be the least-cost option, because a range of other options are available including the use of low sulfur crudes at the refinery, and desulfurization of diesel fuel.[6]

3. Dealing with risk and uncertainty. The analytical framework needs to be modified to permit a more formal treatment of the many uncertainties involved. Even a very simple decision- tree approach can be very useful in providing guidance on the robustness of policy options to risk and uncertainty.

Notes

[1] It is in fact quite routine for governments to engage international consultants as independent reviewers and advisors when dealing with area of expertise that may be unfamiliar. For example, the Government of Indonesia engaged White and Case, an American law firm, and, with World bank assistance, Lahmeyer International, a German engineering firm, to help in the evaluation of studies and proposals for the first private power project in Indonesia (the Paiton coal project in Java).

[2] National Environmental Action Plan 1992-1996, Ministry of Environment and Parliamentary Affairs, October 1991. This calls for the establishment of an environmental cell within the CEB, and a work programme to provide studies and staff training. This task is assigned an "immediate" priority (p.72).

[3] However, whether such approaches will in fact have the anticipated impact remains to be seen.

[4] A good model for what seems indicated for Sri Lanka was recently completed in India, where a comprehensive evaluation of DSM options was undertaken as part of the World Bank-USAID Power Sector Review. The options examined included a diversity of measures from the rehabilitation of agricultural pumpsets to high efficiency industrial motors. Clearly the efficacy of different measures will vary considerably from country to country depending on the devices used in agricultural and industrial sectors. For details of the India analysis, see P. Meier, *India Power Sector Review: Demand Forecasting and Investment Planning*, Office of Energy, USAID, June 1991.

[5] Indeed, one might well question whether FBC is really that much more sophisticated than a PC plant with an FGD system, which also requires considerable expertize to operate satisfactorily. Certainly there would be no reason not to consider PFBC is the Trincomalee coal project is to be implemented as a private power project on a biuld-own-operate (BOO) basis.

[6] A series of refinery modifications were undertaken over the past few years that permit a higher fraction of Malaysian crudes to be used. These are low-sulfur, and produce a larger fraction of low-sulfur middle distillates without the need for desulfurization processing. Thus over the past few years, the actual sulfur content of auto diesel has been significantly below the specification value.

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Annex

The Model

A variety of different modeling approaches were examined for use in this case study. A first decision related to how the trade-off curves would be generated: even though a number of existing optimization models appear suited to either the constraint or the weighting method,[1] we rejected the mathematical programming approach in favor of direct simulation.[2] The most important reason is that we are interested in not just the non-inferior set, but also those solutions that are near this curve, and in particular the plans in the knee sets. Yet solutions that are close to the optimum are not normally generated by the linear programming (LP) software packages commercially available for microcomputers.[3] Of course all such algorithms will pass through near-optimal solutions as they make their way through the solution space, but to examine these intermediate solutions individually is not generally possible.

The direct simulation model has a number of advantages for practical policy making that offset the problem of not being sure that all of the points in the non-inferior set have in fact been identified. Besides the ability to be able to identify knee sets, one may also be interested in identifying very poor programs and policy packages, namely those that never occur in any of the knee sets, and which should be recommended for exclusion from any further consideration by decision-makers.

The main requirement, therefore, is for a model that can examine very quickly perhaps several hundred different expansion plan variants, given the very large number of combinations of different site locations, pollution abatement options, and technology variations. The use of a complex engineering model such as WASP or EGEAS is simply unsuited for the sort of sensitivity analyses required here.[4] This is not to deny the important role that such models have in the planning process: it is simply a matter of choosing a modeling approach that is appropriate to the particular objectives of the planning study at hand.

Candidate models

Several existing models were reviewed as possible candidates for our case study, including:

1. GEMIS/TEMIS, developed in Germany.
2. MIDAS, developed by EPRI.
3. PROSCREEN/PROVIEW/PROMOD, developed by Energy Management Associates.
4. ENPEP/IMPACTS, developed at Argonne National Laboratory.
5. EGEAS/COMPASS, developed by EPRI and the Synergic Resources Corporation.
6. LEAP, developed for the Beijer Institute of Sweden.

Each is reviewed very briefly below. One might note that a full review of all of the various electric systems planning models is beyond the scope of this report,[5] and our concerns here are limited to the extent to which these models satisfy three criteria:

1. Suitability as a research tool? (how easily can modifications be made)
2. Suitability to developing countries?
3. Adequacy of the electric systems representation?

GEMIS/TEMIS:

GEMIS, (for "Gesamt Emissions Modell Integrierter Systeme") was developed in 1987 to 1989 at the OKO Institute and the University of Kassel in Germany.[6] An English version of the model, known as TEMIS (for "Total Emission Model for Integrated Systems") was developed in 1990 with support from the US Department of Energy. The model provides a total fuel cycle analysis of residuals -- in which residuals are calculated in a consistent way from the point of fuel extraction to the point of use. In the genealogy of models, TEMIS is a direct descendant of the SEAS model (Strategic Environmental Assessment System) developed by EPA in the early 1970s, perhaps the first model of this type, and which was used by the US Department of Energy in the late 1970s to evaluate the environmental "impacts" of the National Energy Plan.[7] TEMIS is now being used as the core of a new modeling system for analyzing the environmental residuals of power system projects called the "Environmental Manual", that is being developed with GTZ support.

While GEMIS could be used to compare the total fuel cycle residuals of, say, a 500Mw coal plant with a 500Mw oil-fired plant, it does not have the capability of providing a rigorous and consistent analysis of a power sector development plan (say of the type provided by WASP in the ENPEP package). Although available for microcomputers, it is programmed in PASCAL, and did not meet the requirement of a package that could be easily modified for the purposes of a research study.

MIDAS

Developed for EPRI, MIDAS is a multiobjective simulation model embedded in a decision analysis framework.[8] Certainly from a utility modeling perspective, this model came fairly close to meeting our needs. On the environmental side, the model keeps track of five residuals, and the latest version (MIDAS "GOLD") has a fairly sophisticated treatment of American regulatory requirements for criteria pollutants.

Figure A.1, taken from the MIDAS user manual, illustrates a typical MIDAS decision tree, in this case illustrating a technology choice problem (coal v. combustion turbine). The objective function used here is present value of customer bills, and the optimization takes the form of a backwards iteration. For each chance fork, the expected values are computed by weighing the outcomes by the probabilities, and at each decision fork, the decision path with the preferable objective function value is selected.

Although MIDAS is very powerful, it does not have the necessary flexibility as a research tool, and extensive modifications would have been necessary to use it effectively in developing countries, particularly on the financial side. In the present version of MIDAS, capacity expansion plans are specified exogenously, and built either in a fixed sequence, or the schedule is advanced or delayed in response to demand changes using a planning reserve margin criterion.[9]

PROMOD/PROSCREEN/PROVIEW

This ensemble of models developed by Energy Management Associates (EMA) of Atlanta (now a subsidiary of EDS) presently sets the industry standard for utility modeling in the US, with some 85 active users. Although the package is extremely powerful, the annual license fee is $100,000 per year,[10] and as a commercial code is not suited as a research tool. Despite its acknowledged strengths, for these reasons we did not consider the model any further.

ENPEP/IMPACTS

The WASP model is widely used in developing countries for capacity expansion optimization -- indeed it has been used for this purpose by the generation planning branch of Sri Lanka's CEB for some years.[11] Argonne National Laboratory has developed a microcomputer version of WASP that has been integrated into a broader energy planning package called ENPEP (for Energy and Power Evaluation Package). This includes a module called IMPACTS which provides the capability for calculating pollution residuals and pollution control costs.[12]

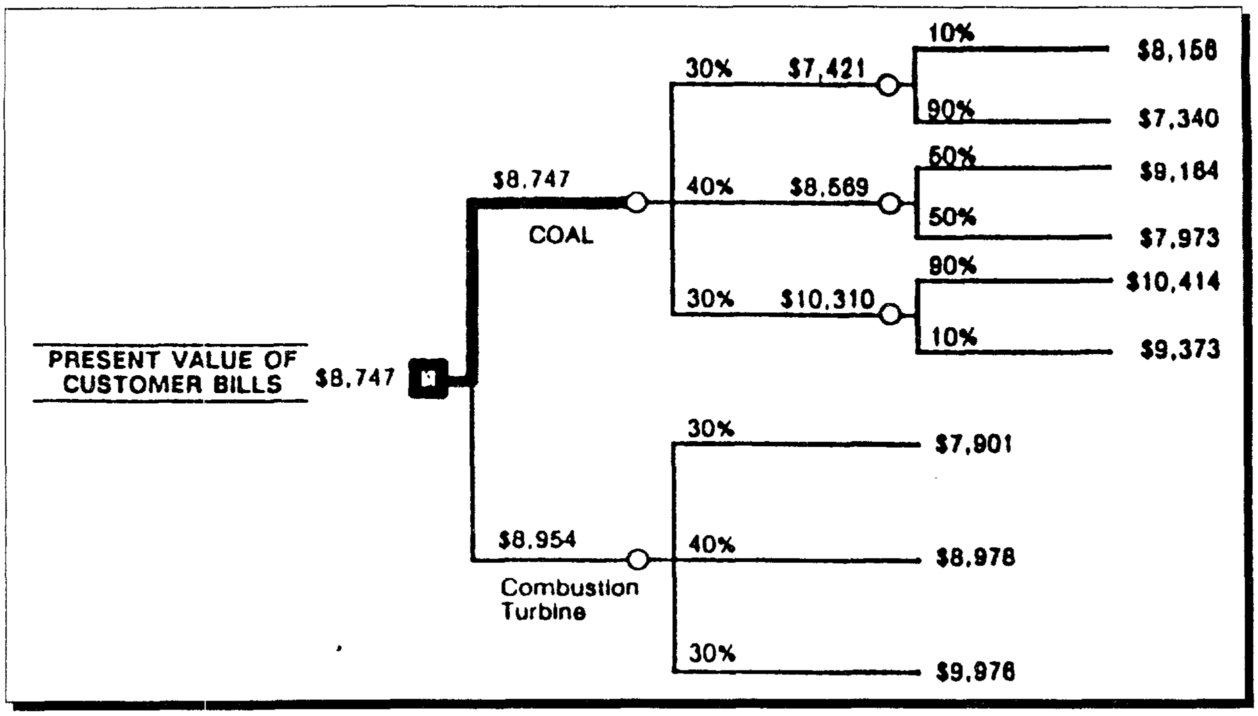

Figure A1: A MIDAS decision tree (from the User Manual, Figure 2.5)

ENPEP also has a broad energy systems analysis capability which can be used to drive the IMPACTS module, and thus provides a similar total fuel cycle emissions inventory as TEMIS. The design philosophy for IMPACTS is summarized by the authors of ENPEP as follows:

> IMPACTS is said to address the "residuals" of the energy system. IMPACTS does not delve into the next steps of a complete environmental assessment by doing calculations of pollutant transport, population exposure or risk assessment. These are better left to other models at this time.

Although IMPACTS is integrated into the ENPEP package, it functions as a post-processor to WASP. Feedbacks to WASP are performed manually by the user.

Even for calculation of residuals, there are important differences in approach between IMPACTS and ENVIROPLAN. For example, in the case of air pollutants, IMPACTS calculates "uncontrolled emissions" as:

UEM_p	$=$	UEF_p	x	E_{in}
uncontrolled emissions of pollutant *p* (kg/year)		emission factor for pollutant *p* (kg/GJ_{in})		energy input (GJ_{in})

IMPACTS then selects a pollution control device based on decision rules that select the lowest cost device to meet a particular regulatory requirement. Subsequently, "controlled emissions" are calculated as:

CEM_p	$=$	UEM_p	x	n
controlled emissions of pollutant *p* (kg/year)		uncontrolled emissions of pollutant *p* (kg/year)		control efficiency

Because many such devices involve substantial changes to net plant heat rates, achieving internal consistency between costs and emission levels on a systemwide basis may therefore require several iterations, involving manual transfer of information back to WASP. ENVIROPLAN, on the other hand, is an integrated simulation model, in which the electric power system simulation calculations,

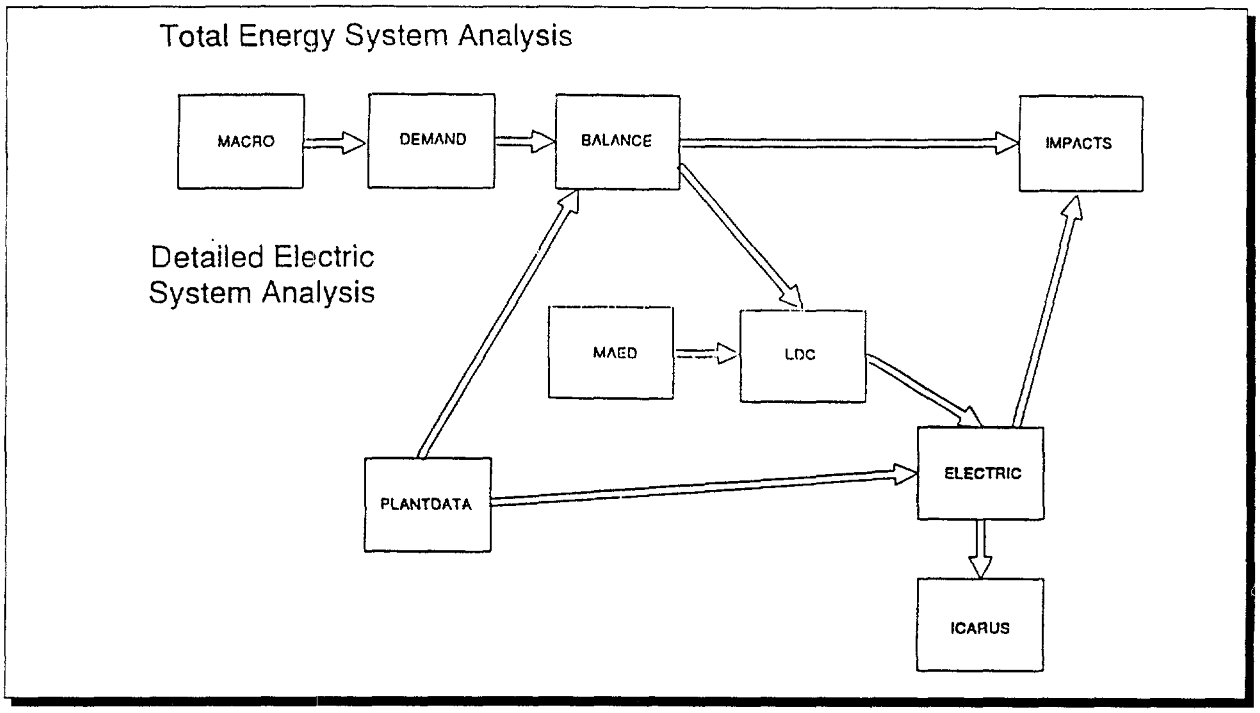

Figure A2: The ENPEP model

including the demand side, are done in the same spreadsheet as the environmental evaluations and financial analysis. Many pollution control options and mitigation measures may involve substantially higher costs, which may in turn have an impact on the tariff, and hence, in turn, on the demand (the so-called "rate feedback" effect). These effects are fully captured by ENVIROPLAN.

EGEAS/COMPASS:

EGEAS is one of the most powerful generation capacity expansion programs available, and is widely used by American utilities.[13] It was developed under EPRI sponsorship and is based on work done at the Massachusetts Institute of Technology: many of the weaknesses of the WASP model are addressed by EGEAS, particularly with respect to hydro plants. The model is currently maintained and distributed by Stone and Webster.[14] EGEAS has been linked with COMPASS, a demand side management model developed by the Synergic Resources Corporation of Philadelphia, and provided with a modern user interface for its new microcomputer version.

To our knowledge, the only developing country that uses EGEAS (in its earlier mainframe version without COMPASS) is India, where the Central Electricity Authority (CEA), which is responsible for generation expansion planning, has used EGEAS since 1985, replacing the WASP model it used previously.

Although EGEAS/COMPASS is an extremely powerful package, it provides only limited capabilities in the environmental area, and is limited to the calculation of residuals (that can however be used as objective functions in the optimization). Both TEMIS and IMPACTS provide a more comprehensive capability to calculate residuals across the entire fuel cycle. Finally, EGEAS/COMPASS is not in the public domain, and is very expensive (except to EPRI members, who get the model at no charge).

LEAP

This model was developed specifically for application to developing countries (LEAP is the acronym for "LDC Energy Alternatives Planning), and provides broad capability to analyze developing country energy issues.[15] It has recently been provided with an environmental database that has comprehensive coverage of emissions factors, and has been applied to a number of developing countries including Kenya, Senegal and Costa Rica.

LEAP is also simulation model The main shortcoming for our purpose is the rather limited characterization of the power sector, which would not have permitted any rigorous analysis of technologies and policies that change the shape of the load duration curve (such as DSM, wind, or the reduction of T&D losses), or to examine supply side options at the project level.

Thus, while each of these models contain some parts of what we needed: none satisfied all of the criteria. Most importantly, none had the direct capability of multi-attribute analysis integrated into a credible characterization of the electric sector, and suitable for extensive sensitivity analysis. And because all involved the use of compiled program environments (PASCAL, FORTRAN, C, etc), modification would have involved considerable programming effort that was beyond the resources of our study.

ENVIROPLAN

In the end we decided to use ENVIROPLAN, a LOTUS 1-2-3 model expressly designed to analyze the environmental impacts of the power sector in a multi-attribute analysis.[16] With most of the calculations performed in a single spreadsheet, including the generation and display of trade-off curves and knee sets, sensitivity analyses that permit the examination of wide ranges of assumptions and policy and program alternatives are relatively easy to conduct. And as a spreadsheet, modifications and enhancements could be easily added as the study progressed.[17] The generation mix expansion algorithm and merit order dispatch calculations are performed in a FORTRAN program that is automatically called by a spreadsheet macro at each iteration of the model.

It should be noted that in ENVIROPLAN, the cost of environmental controls is always consistent, because the integrated calculation ensures that the system demand is always met. Thus, for example, if FGD systems are specified for certain coal burning power plants, ENVIROPLAN will build additional capacity, and/or adjust the dispatch to make up for the Mw and kwh losses associated with FGD systems. Further, these calculations automatically account for the systemwide cost and emission impacts of FGD system installation.

The overall modeling framework is depicted on Figure A.3. The most important hierarchical linkage is with WASP, to which ENVIROPLAN is closely calibrated in order to ensure compatibility of our study to the expansion plan alternatives defined by CEB. Detailed environmental models, such as the air quality model described in the Chapter 8, are also part of the ENVIROPLAN package.

The main features of ENVIROPLAN model itself are indicated on Figure A.4. The process starts with the demand projection, for which several options are available. The first option permits the use of the official CEB forecasts. The second is an econometric model that permits full consideration of rate feedback. The third permits a more detailed projection by end-use (in the manner of the MAED or LEAP models, but with the flexibility to incorporate price effects. In this study, we used only the first option.[18]

The annual load duration curve is then adjusted for demand side management measures (such as the fluorescent lighting program to be described in the next chapter) and wind energy (which, as a non-dispatchable technology, is treated in the usual way as negative demand).

The demand curve is then adjusted for T&D losses to derive the system load curve. In the base case this is aligned to the CEB forecast: the subsequent perturbations of the demand curve that result from wind or DSM measures, however, will have the effect of changing the

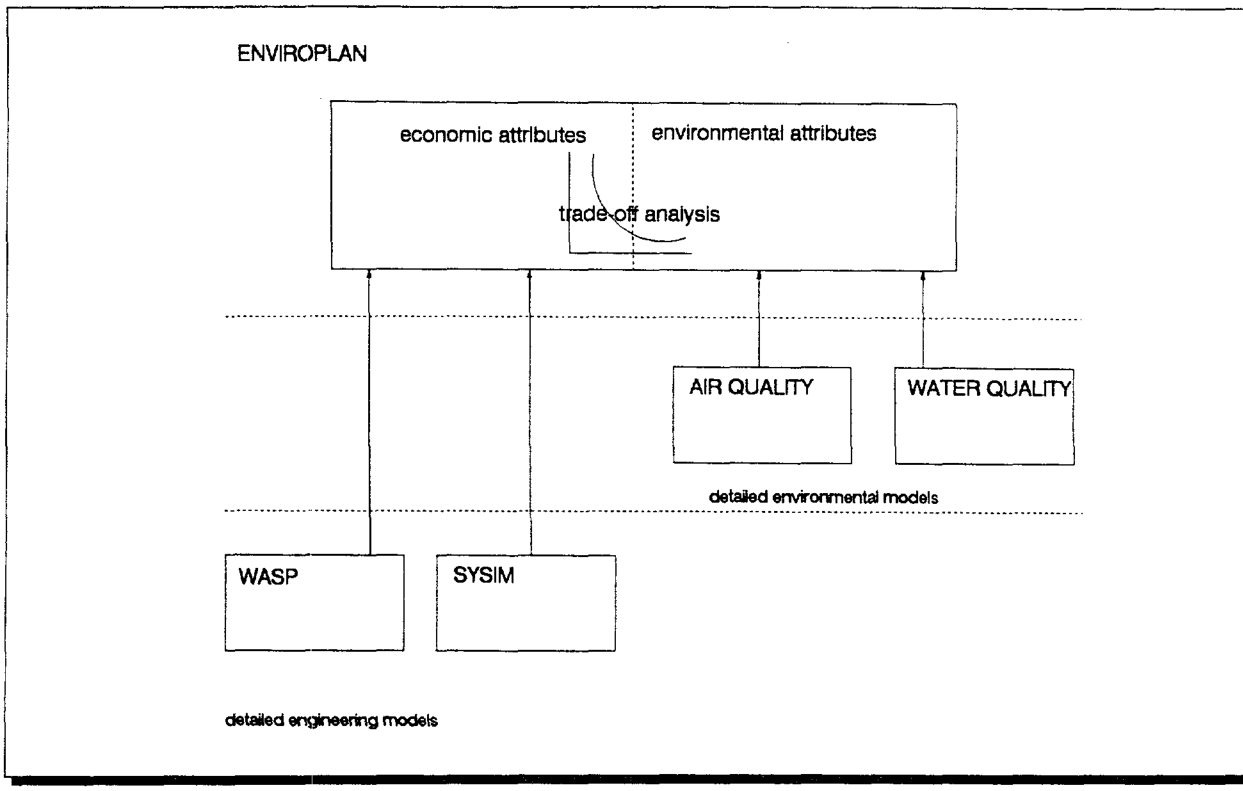

Figure A3: The modelling framework

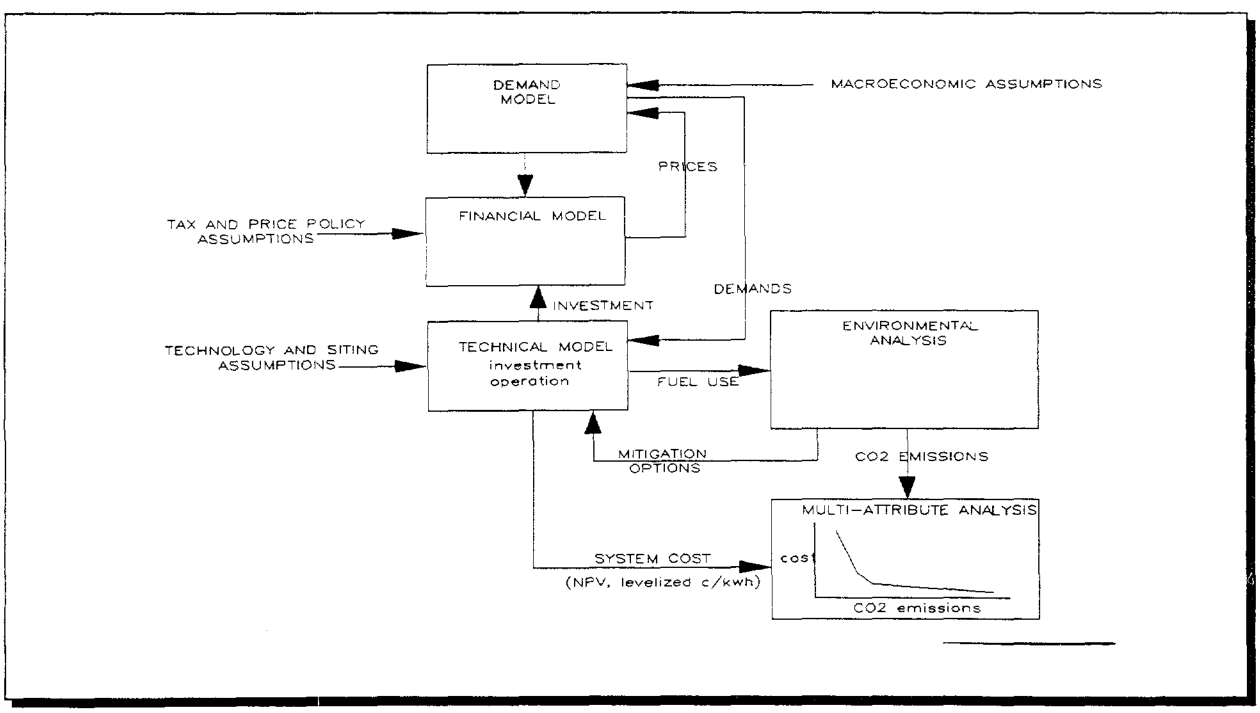

Figure A4: The major features of ENVIROPLAN

base case assumption.

The power plant database for basic economic and technical performance parameters also corresponds exactly to that used by CEB for its generation planning studies.

Generation capacity expansion is based on the anticipated peak load plus some reserve margin. ENVIROPLAN has several available generation expansion algorithms, which are described in detail in the User Manual. In a first "fixed" mode, start-up dates can be aligned exactly to the CEB's WASP results.

The second mode, called "adjusted", builds plants in the same sequence as WASP, but adjusts the timing in such a way as to maintain an exogenously specified planning reserve margin. This is of course a much less sophisticated approach than the probabilistic dynamic programming of WASP that provides an optimization subject to loss of load probability (LOLP) constraints; however, experience indicates that this provides a reasonable approximation if the changes to the load curve are small. Thus, as we perturb the original load curve, say to provide for energy conservation, ENVIROPLAN will defer the construction sequence in light of the lower peak demands. These two capacity expansion modes are exactly the same as the two procedures presently available in MIDAS.

These concepts are illustrated on Figure A.5. The "target margin" is the smoothed "actual" (5-period) reserve margin as yielded by the WASP solution. The "minimum reserve margin" is what is used as the expansion criterion by the "adjusted " algorithm: the next plant is added if the reserve margin would otherwise drop below this minimum level.

However, the expansion path is iteratively adjusted in such a way as also to meet a maximum unserved energy requirement, taken here as 1% of total annual energy. That is, if after merit order dispatch, the unserved energy exceeds this minimum in any year, the target margin is increased incrementally for that year, and the expansion calculations are repeated. This iterative scheme is depicted on Figure A.6.

The third mode, called "cost", builds plants in the ranked order of specific costs. This is the indicated mode if fuel prices change. Constraints can be imposed on the sequence of plant additions (for example, one can force in the Mawella coal plants before Trincomalee, even though the latter have lower specific costs). This mode, which is essential for the analysis of the impacts of fuel price changes, or fuel taxes,

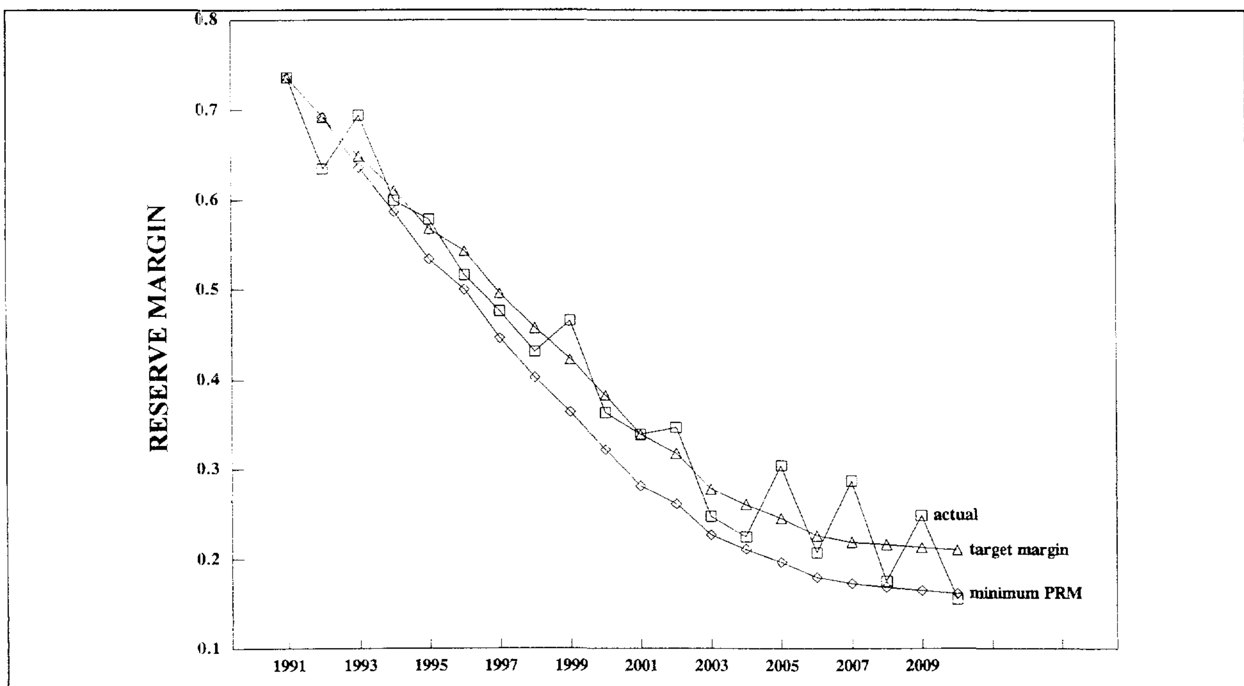

Figure A5: Reserve margins

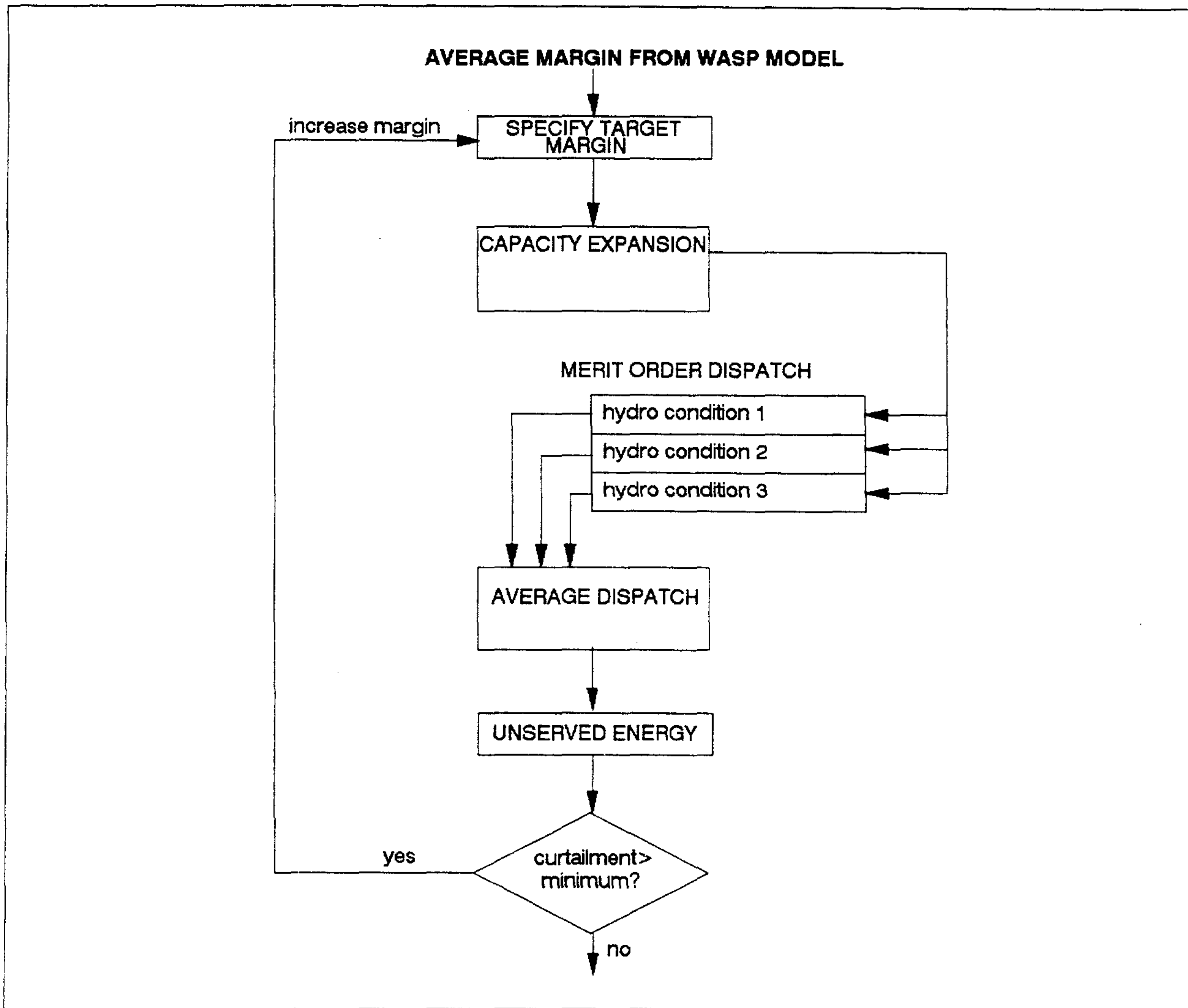

Figure A6: The capacity expansion algorithm

is not presently available in MIDAS, and is one of the reasons why MIDAS was not selected.[19]

ENVIROPLAN makes merit order dispatch calculations for each of the three hydro conditions used by the CEB for WASP simulations, and the "average" dispatch, which is used to calculate fuel consumption and pollutant emissions from thermal plants, is then the weighted sum of the three individual dispatch conditions. This will provide a much better alignment of ENVIROPLAN to WASP than the much simpler procedure of dispatching into "average" hydro conditions.

The merit order itself is calculated in the usual way by incremental marginal cost. ENVIROPLAN may yield a marginally lower estimate of fuel consumption for thermal plants because fuel consumption is calculated at the full load heat rate; we do not distinguish between heat rate at minimum load and the incremental heat rate as does WASP.

In general, ENVIROPLAN solutions give somewhat higher levelized costs per kwh. There is a major difference for those variants where hydro plants are forced into the solution: for example, with Upper Kotmale forced into the WASP solution, WASP indicates a levelized cost that is .15c/kwh more expensive, while ENVIROPLAN gives a value that is slightly lower than the base case.

Figure A.7 shows a comparison of the total installed capacity between the WASP results (simulated by the "fixed" option), and the "adjusted" expansion path in which plants are

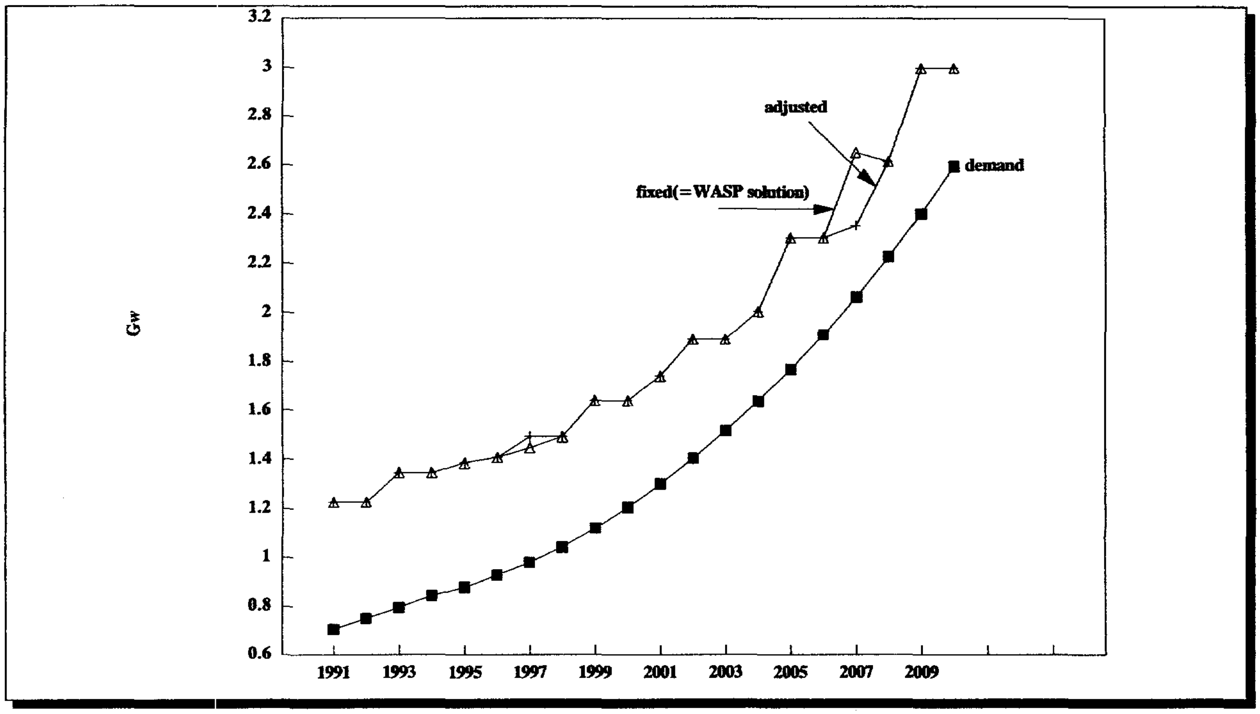

Figure A7: Expansion plan comparisons

added in such a way to meet the minimum reserve margin target. The solutions are seen to be essentially identical, except for 1997 and 2007, where ENVIROPLAN has advanced, and delayed by one year, one unit, respectively.

Notes

[1] See Annex II to Chapter 6

[2] One LP model in particular that has multi-objective capability is MARKAL. Developed as a mainframe model fifteen years ago for the International Energy Agency to examine long-term energy R&D strategies, it has recently been moved to a microcomputer environment and has seen new use in the United States to examine the implications of CO_2 emissions reduction strategies. The model has also been used in some developing countries, notably Indonesia. Whatever the merits of the new user-interface, we viewed this model as being simply too unwieldy for application to our study. For an overview of the model, see e.g. L. Fishbone and H. Abilock, MARKAL, a linear-programming model for energy systems analysis: technical description of the BNL version, Energy Research, 5, pp.369-379, 1981. More recently the model has been linked to the MACRO model developed at Standford by Prof. A. Manne, and rewritten into the GAMS programming environment: see e.g. L. Hamilton *et al.*, *MARKAL-MACRO: An overview*, Report BNL-48377, Brookhaven National Laboratory, Upton, NY, 1992.

[3] Recently, some approaches have been developed that do generate such near-optimal solutions -- e.g. V. Lofti, T.J. Stuart and S. Zionts, An aspiration-level interaction model for multiple criteria decision-making, Working Paper #711, Department of Management Science and Systems, School of Management, SUNY Buffalo, 1990. But these are still at the research stage, and the software still lacks the sort of comprehensive documentation necessary for general dissemination.

[4] In any event, a second problem with the existing models such as WASP concerns their scope: while they provide great detail on the supply side, they have very limited capability of examining demand side issues beyond simply using alternative exogenously specified load forecasts. IAEA, who supports the WASP model, does provide a demand side model for use with WASP called MAED: but this model is not currently installed in Sri Lanka. Moreover, even if it *were* available, the MAED-WASP combination is still very cumbersome, and ill suited to the particular requirements of our case study. Nevertheless, WASP is an extremely useful model, and, as noted earlier, is used for generation system expansion planning in Sri Lanka (as well as in a number of other countries as well).

[5] For a complete review of electric systems models (but without any discussion of environmental analysis capabilities), the reader is directed to Y. Albouy and Systems Europe, *Assessment of electric power system planning models*, Energy Department Paper 20, World Bank, Washington, DC, 1985. A. Markandya, Environmental costs and power system planning, Utilities Policy, 1, p.13-27, 1990, provides a review of the environmental aspects of electric systems models.

[6] OKO Institute, *Umweltanayse von Energie Systemen: Gesamt- EmissionsModell Integrierter Systems (GEMIS)*, Ministry for Economy and Technology of Hessen, Darmstadt, 1989.

[7] See e.g. *National Environmental Impact Projection II*, US Department of Energy, Office of Environmental Assessment, March 1980.

[8] However, relatively few utilities actually use the decision analysis part of the model. The model is supplied to EPRI members free of charge, but 24 utilities pay the $5000/year for membership in the User Group, and can be regarded as serious users of the model.

[9] This is explained below in the discussion of ENVIROPLAN.

[10] According to an EMA source, the only reported licensee in a developing country is the National Power Corporation of the Philippines.

[11] Few, if any, American utilities still use WASP. Many of those that did use the model, such as Duke Power, have recently acquired PROMOD.

[12] W. Buehring *et al.*, ENPEP: *An integrated approach for modeling national energy systems*, Argonne National Laboratory, Environmental Assessment and Information Sciences Division, 1991.

[13] About 40 major utilities use the model as their main capacity expansion planning tool

[14] For a brief description see, e.g., Stone & Webster Management Consultants, Inc., *Least Cost Planning using EGEAS/COMPASS/ STAFF*, Boston, Mass., 1989. For a more detailed description, see

EGEAS Capabilities Manual, April 1989, also available from Stone and Webster.

[15] P. Raskin, *LEAP, a Microcomputer System for Energy Planning*, in Microcomputer Applications for Energy Planning in Developing Countries, United Nations, New York, 1985.

[16] P. Meier, *ENVIROPLAN: A multi-attribute environmental simulation model for energy and power systems planning*, Environment Department, World Bank, Washington, DC, 1994.

[17] ENVIROPLAN runs in version 3.4 of LOTUS 1-2-3. In contrast to versions 1 and 2, in version 3.4 spreadsheet size is constrained only by total memory available, and no longer makes any distinction between conventional and extended and expanded memory.

[18] The impact of price and tax policy, in which we used the econometric demand specification, is reported in a subsequent study: see P. Meier, M. Munasinghe and T. Siyambalapitiya, Energy sector policy and the environment: A case study of Sri Lanka, Environment Department, World Bank, December 1993.

[19] We understand from the MIDAS user group that the addition of such a capability to MIDAS is presently being considered.

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