MULTI-ATTRIBUTE DEISION ANALYSIS FOR ENVIRONMENTAL ANALYSIS OF POWER SYSTEM EXPANSION

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BACKGROUND

The environmental impacts of power system development are widely recognized, and have become an increasingly important topic of public debate in both the developed and the developing countries. In the developing countries, this trend is part of a broader emerging concern over the relationship between sustainable development and environmental costs(1); and donor agencies and the International Financial Institutions have become increasingly concerned about implementing new policies that respond more effectively to environmental goals.(2) Indeed, there is general agreement that the environmental impacts of power systems need to be considered more fully than in the past(3), and that the most pressing need is to incorporate environmental concerns into investment planning and decision-making rather than simply reacting to environmental problems after they occur(4).

But 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. Most of the attention to date has been given to improving procedures at the project level, and 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 an environmental impact statement (EIS) and a benefit/cost analysis at the project level can address many of the most important environmental issues. The project level EIS deals well with local, site specific questions, and the options for project level mitigation (such as resettlement questions at dams, loss of wildlife habitat, local socio-economic impacts associated with construction). However, the project level EIS deals poorly with regional (e.g. downstream water quality impacts), national (e.g. acid rain) and global scale (e.g. greenhouse gas) issues. These can really only be addressed quantitatively if the spatial scope of analysis matches the geographical area over which impacts are felt. This means an examination not merely of the single project, but of all the projects that make up a sectoral plan. The fundamental question here is not whether the impact of the current project is environmentally acceptable -- almost invariably one can show that the marginal impact of a single plant is environmentally acceptable -- but whether the cumulative impact of a particular development path, that may include several such facilities, is acceptable (5).

In response to the need to move from qualitative discussion of such issues to quantitative procedures, the Environmental Policy Research Division of the World Bank has initiated a research program to explore alternative approaches to quantifying environmental costs and benefits in a number of different sectors. 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.

This applied research program for the power sector takes the form of a series of case studies, of which Sri Lanka is the first. We believe the case study approach to be particularly appropriate for this kind of study, insofar as there already exists a vast theoretical literature on the subject, and a great deal of experience in the developed countries. In the case of Sri Lanka, the goal of the research study is to examine the practicality of using multi-attribute decision analysis in a developing country setting, and to demonstrate the usefulness of such techniques as a way of better incorporating environmental goals into power sector decision-making.

CURRENT POWER SYSTEM PLANNING PROCEDURES

In the past, the principal planning objective has been to deliver the anticipated need for electrical energy at least cost to the entity delivering power. 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

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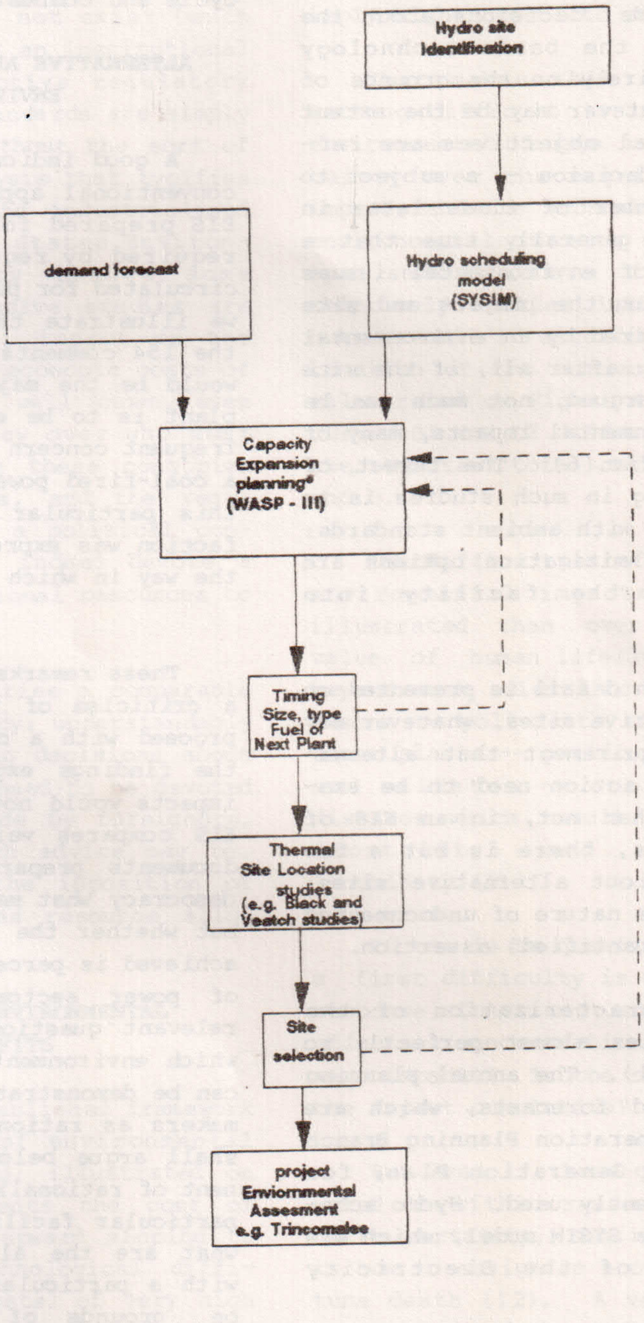


Figure 1: The Power System Planning Process in Sri Lanka.

"least cost" plan. In practice this has meant the application of capacity expansion optimization models, 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.

Environmental considerations are generally deferred to at least the siting stage of the process. In other words, decisions about the generation mix, and the basic technology choices, are made entirely on the grounds of direct costs. And whatever may be the extent to which environmental objectives are reflected in the siting decision -- a subject to which we return a number of times later in this paper -- it is generally true that a detailed examination of environmental issues is conducted only during the project and site specific analysis required by an environmental impact statement (EIS): after all, if the site is not known, it is argued, not much can be done to predict environmental impacts, many of which are site specific.(6) The thrust of environmental modelling in such studies is to demonstrate compliance with ambient standards: if these are not met, mitigation options are explored to bring the facility into compliance.

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 EIS of several hundred pages, there is but a few pages of discussion about alternative sites: most of which is in the nature of undocumented (and almost always unquantified) assertion.

This general characterization of the planning process applies almost perfectly to Sri Lanka (see Figure 1). 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 WASP-III is currently used. Hydro scheduling is done with the SYSIM model, which was developed as part of the Electricity Masterplan(7).

In the early 1980s when it was first determined that there was a need for baseload thermal stations once the better hydro sites were exhausted, Black and Veatch were commissioned to conduct a siting study for a coal fired power station. The first stage screening resulted in the selection of the Trincomalee area as the best general location, followed by a detailed screening of the Trincomalee Harbor area that resulted in selection of a site on Clappenburg Bay.(8) This was followed by a detailed Social and Environmental Impact Assessment of the Trincomalee site. Somewhat later, in light of the controversy over the Trincomalee site, a broader siting study was undertaken to include examination of locations for diesel, steam cycle coal and oil, combined cycle and combustion turbines.(9)

ALTERNATIVE APPROACHES TO INCORPORATING ENVIRONMENTAL CONCERNS

A good indicator of the inadequacy of the conventional approach is the reaction to the EIS prepared for the Trincomalee plant. As required by regulations, this document was circulated for public comment, and on Figure 2 we illustrate the results of an analysis of the 154 comments received. That air quality would be the major concern over 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. Widespread dissatisfaction was expressed by NGOs and others over the way in which decisions had been reached.

These remarks should not be interpreted as a criticism of the CEB, of the decision to proceed with a coal-fired power plant, or of the findings expressed in the EIS that the impacts would not be significant: indeed, the EIS compares very favorably with comparable documents prepared elsewhere. However, in a democracy what matters is not just the result, but whether the process by which a result is achieved is perceived to be fair. In the case of power sector development decisions, the relevant question is whether the process by which environmental objectives are considered can be demonstrated to non-technical decision-makers as rational and demonstrable. As we shall argue below, the most important component of rationality is that a decision about a particular facility is made on the basis of what are the alternatives: not to proceed with a particular plant at a particular site on grounds of unacceptable environmental impact is not rational unless the impacts of building the plant elsewhere, or building a plant of a different technology, are considered on an equal basis.

One approach that is clearly inappropriate is to justify a particular option on grounds that all applicable environmental regulations have been complied with. Even in the industrialized countries, where the regulatory framework is well developed, with relatively well tested enforcement mechanisms, this presumption is questionable. Phrases such as "impacts are insignificant, and in any event full compliance with all applicable standards ensures that environmental impacts are acceptable" are commonplace in EISs everywhere.

In most developing countries, however, comprehensive standards do not exist (much less does there usually exist an institutional framework capable of effective regulatory enforcement). Very often standards are simply borrowed from elsewhere, without the sort of exhaustive cost-benefit analysis that typifies the regulatory process in the industrialized countries. When the United States Environmental Protection Agency issues some particular regulation, extensive studies are conducted on the potential impact on the affected industries, and the economic costs of the regulation are generally well known, even if there remains controversy over who must bear the cost. Moreover, in these countries the basis of such standards, and the regulations to enforce them, is a political consensus that the nation can indeed devote a substantial share of its national resources to environmental protection.

In most developing countries a comparable debate is still in its infancy; understandably there is resistance to having decisions about the share of resources that need to be devoted to the environment being made by foreigners, however well-intentioned such advice may be. The point is simply that the imposition of standards necessarily implies resource allocation decisions.

ECONOMIC VALUATION OF ENVIRONMENTAL COSTS AND BENEFITS

There is a very well established framework for including the costs of environmental damages into decision making, illustrated on Figure 3. Curve X represents the cost of pollution abatement: it is upward sloping to reflect the increasing technological difficulties (and hence higher costs) of very high pollutant removal efficiencies. Curve Y 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. Nonlinearities 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 (X+Y); generally this curve would exhibit a minimum somewhere within the range of technologically feasible pollution abatement options.

In the ideal case a discussion of appropriate standards would take cognizance of this total cost curve: in case of Figure 3, one would wish to fix the standard at A. Standards both more stringent, and less stringent, imply higher costs to society.

What makes this approach to standard setting difficult is the uncertainty in the environmental damage cost function. Uncertainty over the magnitude of the physical impact, and the economic consequences of such environmental concerns such as global warming, span several orders of magnitude. Yet even relatively smaller differences in the damage curve result in significant differences in the location of the minimum cost point. This is illustrated on Figure 4, where the two damage curves D1 and D2 differ by a factor of 2, with the resultant total cost minima indicated at A and B.

The difficulties of economic valuation of environmental impacts are nowhere better illustrated than over the question of the value of human life(10). It is established beyond much scientific doubt 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)(11).

If one is to quantify the health effects, a first difficulty is quantifying the dose-response function: are there any threshold effects (concentrations below which here is zero impact)? Is the relationship linear? Is the impact cumulative?

But even if these questions could be answered to within reasonable bounds of scientific certainty, the more formidable problem is how to assign an economic value to a premature death (12). A variety of methods have been suggested for this purpose, ranging from estimates of the discounted value of lost earnings (13) to surveys of the amounts in jury awards in damage suits involving death or disabling injuries. None of the available methods seems 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

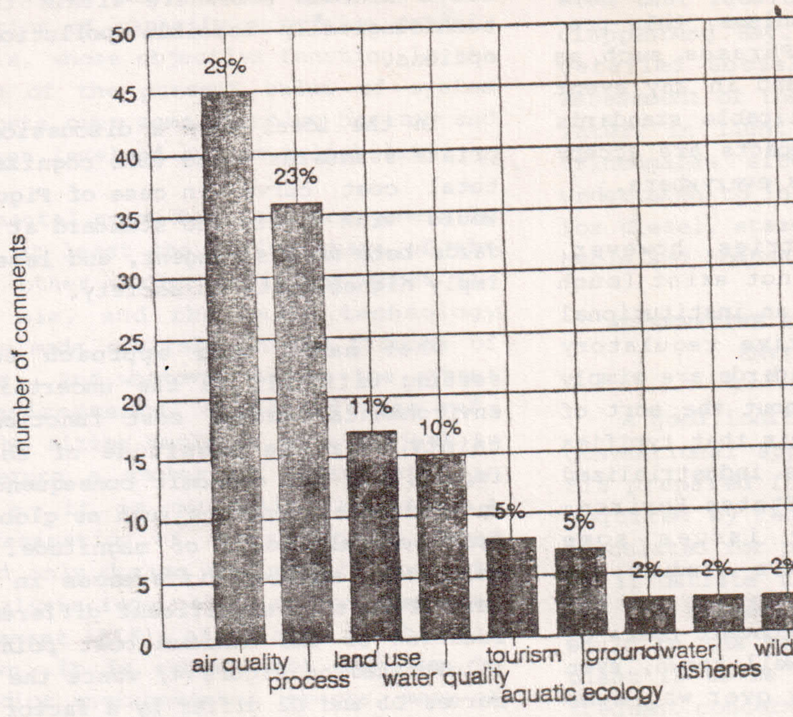


Figure 2: Public comments to the Trincomalee EIS.

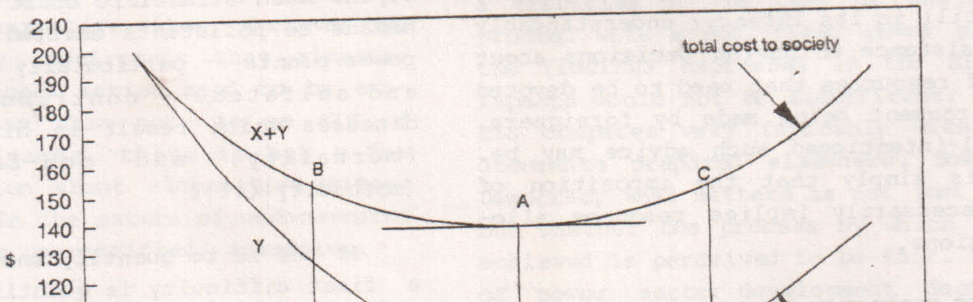


Figure 3: Optimum level of pollution abatement.

Table 1: Value of inundated land at potential hydro sites

Site	project cost,$m (1)	value of land inundated (2)	fraction (2)/(1)
MADU003	63	0.055	0.08%
KOTM033	92	0.199	0.2%

(1) total capital and operating costs over a 50year lifetime, using a 10% discount rate.

(2) present value of forest and agricultural land inundated, over 50year lifetime at 10%.

Source: GTZ, Masterplan for the Electricity Supply of Sri Lanka

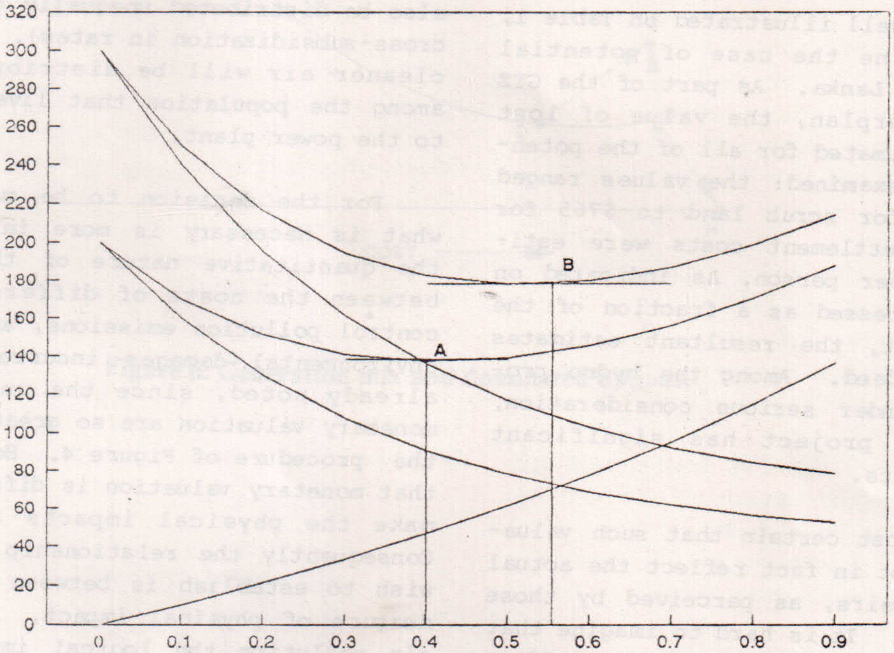


Figure 4: The impact of uncertainty in damage cost estim

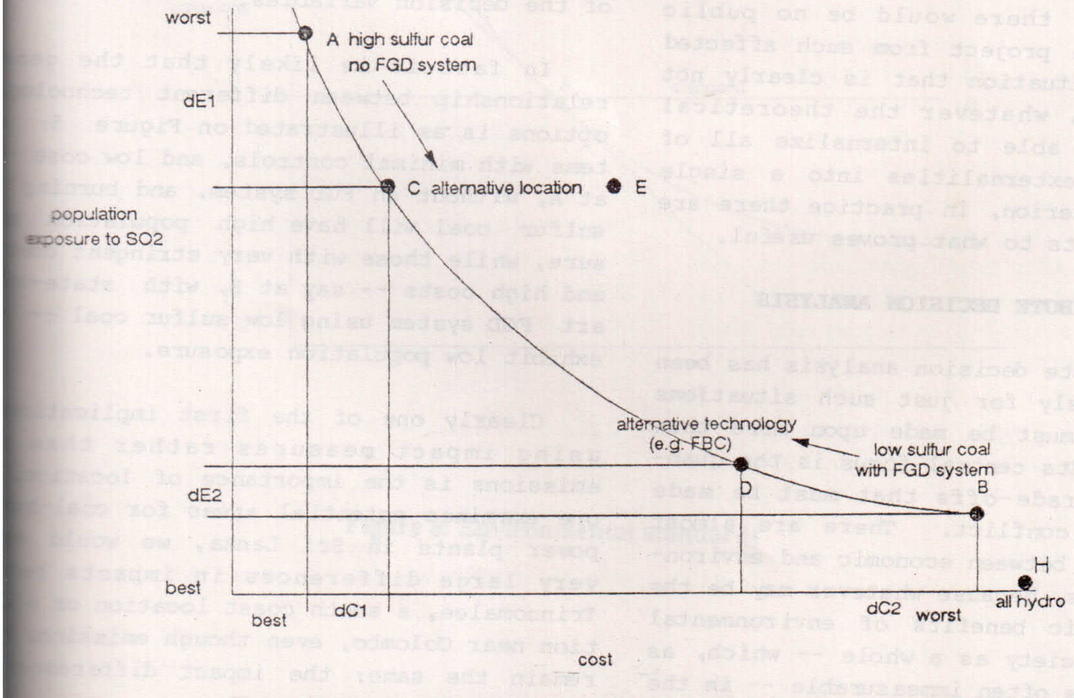


Figure 5: Trade-offs between cost and population exposure to air pollution.

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. However, it is probably fair to assert that (1) the more significant the impact, the more difficult it is to value (as exemplified by the ultimate impact of death), and (2) those impacts that can be readily valued result in very small changes to the economic decision calculus.

This point is well illustrated on Table 1, 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 $765 for coconut land; resettlement costs were estimated at $US1500 per person. As indicated on Table 1, when expressed as a fraction of the total project cost, the resultant estimates are very small indeed. Among the hydro projects presently under serious consideration, only the Kukule project has significant resettlement impacts.

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. 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. 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 proves useful.

MULTI-ATTRIBUTE DECISION ANALYSIS

Multi-attribute decision analysis has been developed expressly for just such situations where decisions must be made upon more than one objective. Its central focus is the quantification of trade-offs that must be made when objectives conflict. There are almost always conflicts between economic and environmental objectives, because whatever may be the long run economic benefits of environmental protection to society as a whole -- which, as noted above, are often immeasurable -- in the short run those who will bear the immediate economic costs of higher levels of environmental protection are not the same as those who receive the benefits.

For example, consider the question of whether or not flue gas desulfurization systems should be installed at a coal burning power station. The additional costs will be borne in the first instance by the electric utility, who will be responsible for financing the higher capital outlays involved. These higher costs are then passed onto the consumers of electricity (a burden that may also be distributed unequally given the usual cross-subsidization in rates). The benefits of cleaner air will be distributed primarily among the population that lives in proximity to the power plant.

For the decision to be made rationally, what is necessary is more information about the quantitative nature of the relationship between the costs of different options to control pollution emissions, and the level of environmental damages incurred. For reasons already noted, since the uncertainties in monetary valuation are so great, we cannot use the procedure of Figure 4. However the fact that monetary valuation is difficult does not make the physical impacts any less real. Consequently the relationship that one would wish to establish is between the cost and measure of physical impact. In the case o air pollution the logical impact measure i the population exposure. In the jargon o decision analysis, cost and population expo sure to air pollutants are the "attributes of the decision variables.

In fact it is likely that the genera relationship between different technologica options is as illustrated on Figure 5: sys tems with minimal controls, and low cost --sa at A, without an FGD system, and burning hig sulfur coal will have high population expo sure, while those with very stringent contro and high costs -- say at B, with state-of-th art FGD system using low sulfur coal -- wil exhibit low population exposure.

Clearly one of the first implications o using impact measures rather than jus emissions is the importance of location. one examines potential areas for coal-burni power plants in Sri Lanka, we would expe very large differences in impacts betwe Trincomalee, a south coast location or a loc tion near Colombo, even though emissions wou remain the same; the impact differences a

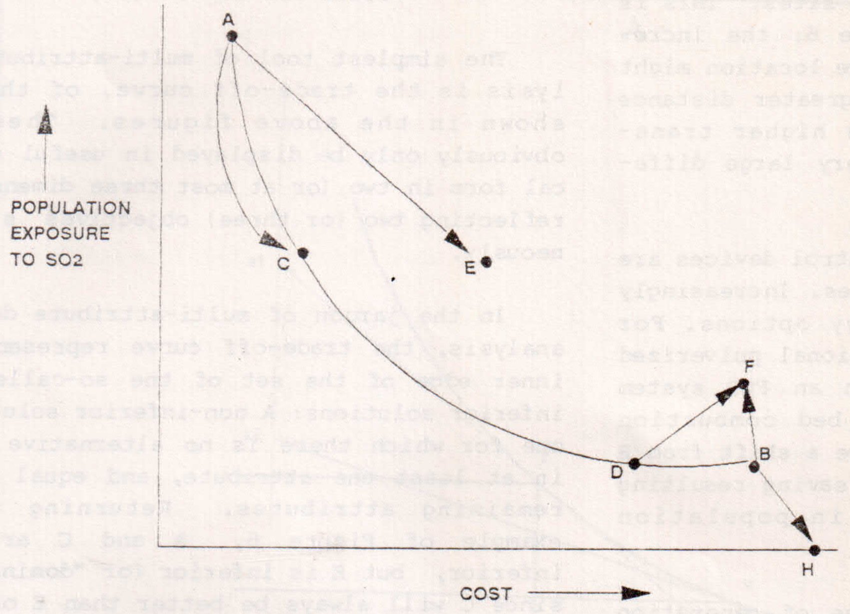


Figure 6: Generation mix and dominated options.

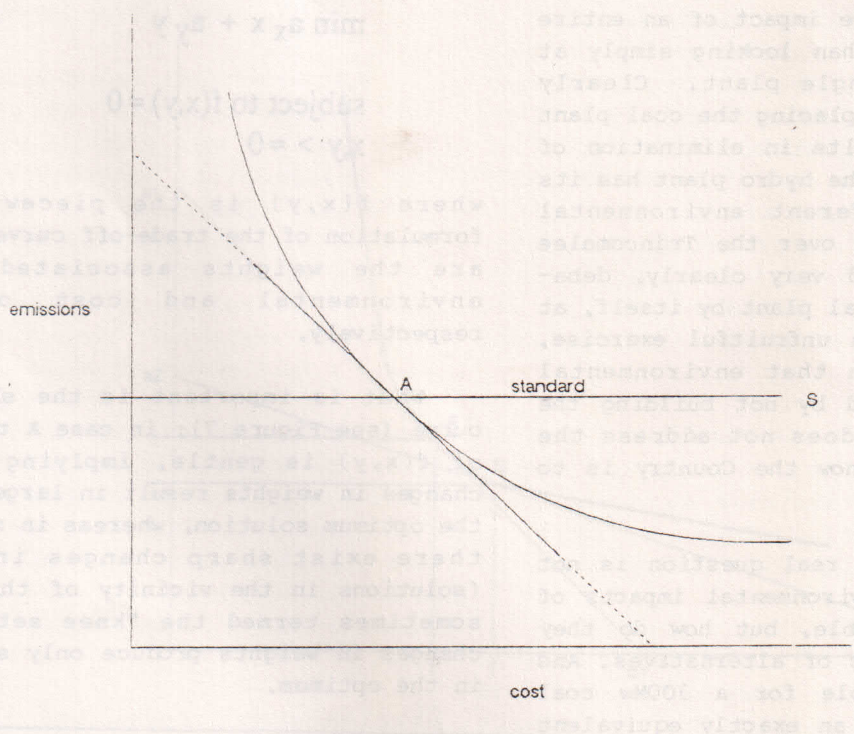


Figure 8: Environmental standards

due to sharp meteorological differences (and wind regimes in particular) as well as obvious differences in population density at given distances from potential plant sites. This is depicted by point C of Figure 6: the incremental costs of the alternative location might be very small (say due to a greater distance from load centers, implying higher transmission costs), but with a very large difference in population exposure.

Location and pollution control devices are not the only possible responses. Increasingly important are new technology options. For example, in place of a conventional pulverized coal-fired boiler fitted with an FGD system one might select fluidized bed combustion technology. This might involve a shift from B to D, with a substantial cost saving resulting in only a small increase in population exposure.

Finally there is the issue of generation mix itself. As indicated on Figure 6, one might be able to attain zero population exposure to SO2 by building a hydro plant instead of the coal plant (at H).

Indeed, this points to the importance of looking at the cumulative impact of an entire expansion plan rather than looking simply at the impacts of the single plant. Clearly while it is true that replacing the coal plant with a hydro plant results in elimination of air pollution impacts, the hydro plant has its own set of very different environmental impacts. As the debate over the Trincomalee coal plants demonstrated very clearly, debating the impacts of a coal plant by itself, at the permit stage, is an unfruitful exercise, because the conclusion that environmental impacts can be minimized by not building the plant, while obvious, does not address the fundamental problem of how the Country is to supply its electricity.

In other words, the real question is not so much whether the environmental impacts of Trincomalee are acceptable, but how do they compare with the impacts of alternatives. And since it is not feasible for a 300Mw coal plant to be replaced by an exactly equivalent 300Mw hydro plant, it is clear that the focus of the environmental debate must be moved to the level of expansion plans. To be sure, there will be site specific issues that must be faced, and specific project level mitigation options to be discussed, quite appropriately, as part of the project level EIA. But the project level EIS is a very poor vehicle to debate the more fundamental technology, fuel and locational options.

Trade-off curves (14)

The simplest tool of multi-attribute analysis is the trade-off curve, of the type shown in the above figures. These can obviously only be displayed in useful graphical form in two (or at most three dimensions), reflecting two (or three) objectives simultaneously.

In the jargon of multi-attribute decision analysis, the trade-off curve represents the inner edge of the set of the so-called non-inferior solutions: A non-inferior solution is one for which there is no alternative better in at least one attribute, and equal in the remaining attributes. Returning to the example of Figure 6, A and C are non-inferior, but E is inferior (or "dominated"), since C will always be better than E on cost, but equal on population exposure.

Once the curve has been established, the next question is to examine the implied weights of particular solution points. Consider, for example, the following LP (15):

$$\min a_x x + a_y y$$

$$\text{subject to } f(x,y) = 0$$

$$x,y >= 0$$

where f(x,y) is the piecewise linear formulation of the trade-off curve, and ax, ay are the weights associated with the environmental and cost objectives, respectively.

What is important is the shape of the curve (see Figure 7): in case A the curvature of f(x,y) is gentle, implying that small changes in weights result in large changes in the optimum solution, whereas in case B, where there exist sharp changes in the curve (solutions in the vicinity of this point are sometimes termed the "knee set"), similar changes in weights produce only small changes in the optimum.

Whether or not such "knee sets" exist is obviously critical to the practical aspects of setting environmental policy: if they do, then particular regulations are much more easily justified than if they do not.

Indeed, setting a standard is in fact equivalent to giving a set of values to the

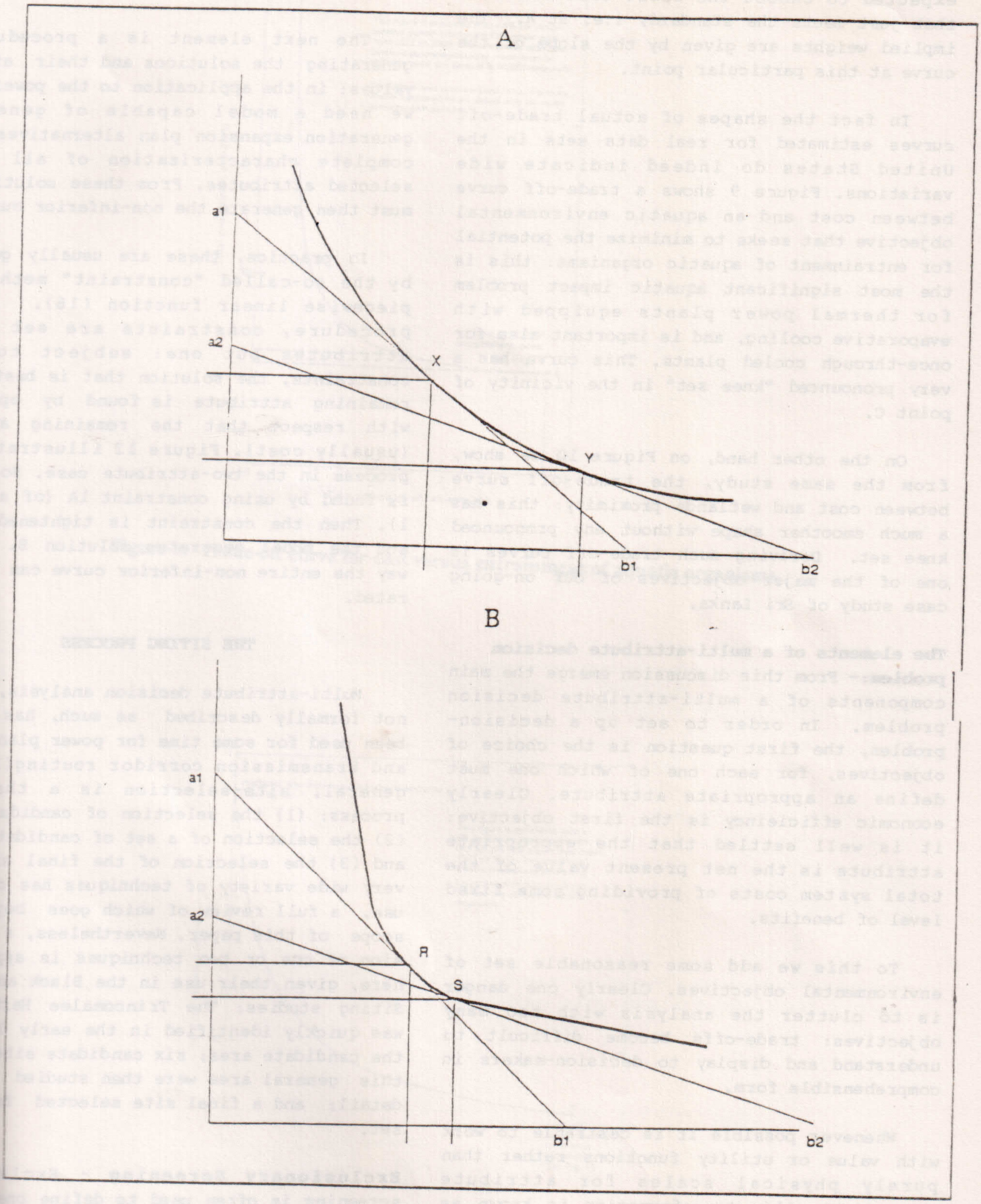


Figure 7: The shape of trade-off curves.

weights. On Figure 8, suppose a standard has been set at S. Utility decision-makers can be expected to choose the least cost solution that just meets the standard, i.e. at A. The implied weights are given by the slope of the curve at this particular point.

In fact the shapes of actual trade-off curves estimated for real data sets in the United States do indeed indicate wide variations. Figure 9 shows a trade-off curve between cost and an aquatic environmental objective that seeks to minimize the potential for entrainment of aquatic organisms: this is the most significant aquatic impact problem for thermal power plants equipped with evaporative cooling, and is important also for once-through cooled plants. This curve has a very pronounced "knee set" in the vicinity of point C.

On the other hand, on Figure 10 we show, from the same study, the trade-off curve between cost and wetlands proximity: this has a much smoother shape without any pronounced knee set. Deriving such trade-off curves is one of the major objectives of our on-going case study of Sri Lanka.

The elements of a multi-attribute decision problem:- From this discussion emerge the main components of a multi-attribute decision problem. In order to set up a decision-problem, the first question is the choice of objectives, for each one of which one must define an appropriate attribute. Clearly economic efficieincy is the first objective: it is well settled that the appropriate attribute is the net present value of the total system costs of providing some fixed level of benefits.

To this we add some reasonable set of environmental objectives. Clearly one danger is to clutter the analysis with too many objectives: trade-offs become difficult to understand and display to decision-makers in comprehensible form.

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 11 we show alternative representations of a scaling rule for aquatic ecosystem damage: the 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 oC produces the same damage as a 1 degree rise from 29 to 30. Attribute value function 2, on the other hand, implies a non-linear response function.

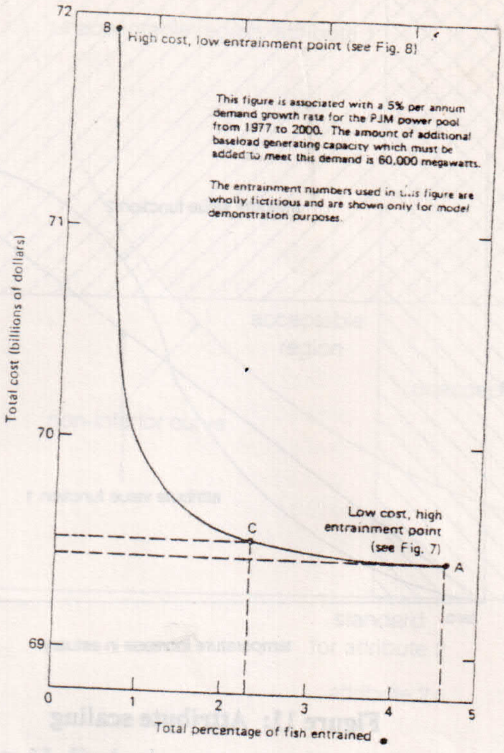
The next element is a procedure for generating the solutions and their attribute values: in the application to the power sector we need a model capable of generating generation expansion plan alternatives with a complete characterization of all of the selected attributes. From these solutions one must then generate the non-inferior curve(s).

In practice, these are usually generated by the so-called "constraint" method as a piecewise linear function (16). In this procedure, constraints are set on all attributes but one: subject to these constraints, the solution that is best in the remaining attribute is found by optimizing with respect that the remaining attribute (usually cost). Figure 12 illustrates this process in the two-attribute case. Solution A is found by using constraint 1A (of attribute 1). Then the constraint is tightened to 1B, and the model generates solution B. In this way the entire non-inferior curve can be generated.

THE SITING PROCESS

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(17). In general, site-selection is a three-step process: (1) the selection of candidate areas (2) the selection of a set of candidate sites, and (3) the selection of the final site. A very wide variety of techniques has come into use, a full review of which goes beyond the scope of this paper. Nevertheless, a discussion of one or two techniques is appropriate here, given their use in the Black and Veatch Siting studies: The Trincomalee Harbor area was quickly identified in the early 1980's as the candidate area; six candidate sites within this general area were then studied in more detail; and a final site selected from this set.

Exclusionary Screening - Exclusionary screening is often used to define one or more candidate areas. In the vocabulary of decision analysis, this is a decision rule in which candidates are rejected if at least one attribute falls below some pre-defined standard (See Figure 13).



This figure is associated with a 5% per annum demand growth rate for the PJM power pool from 1977 to 2000. The amount of additional baseload generating capacity which must be added to meet this demand is 60,000 megawatts.

The entrainment numbers used in this figure are wholly fictitious and are shown only for model demonstration purposes.

Figure 9: Trade-off curve for cost versus entrainment of aquatic organisms.

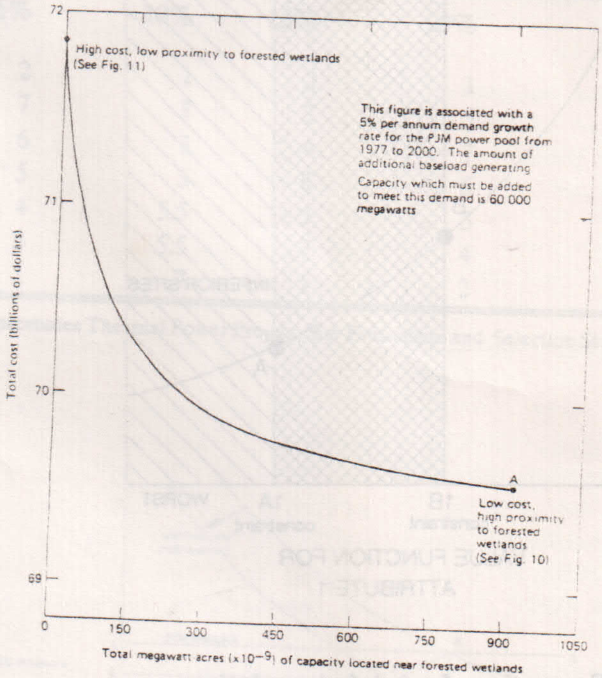


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Figure 10: Tradeoff curve between cost and wetlands proximity.

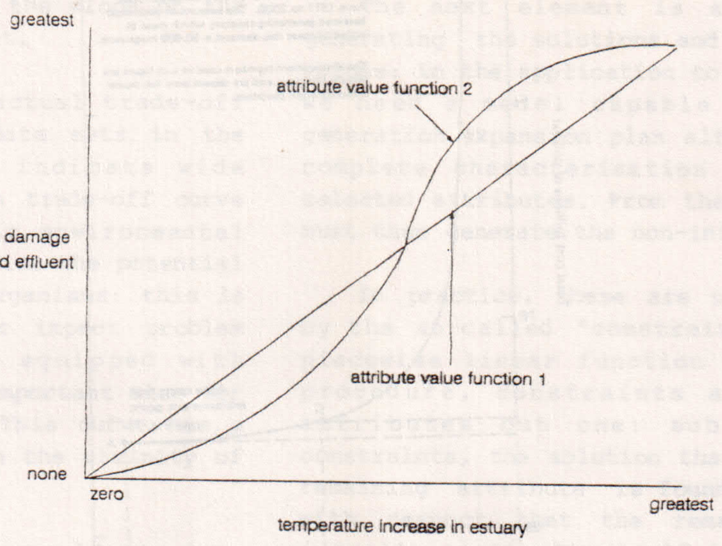

Figure 11: Attribute scaling

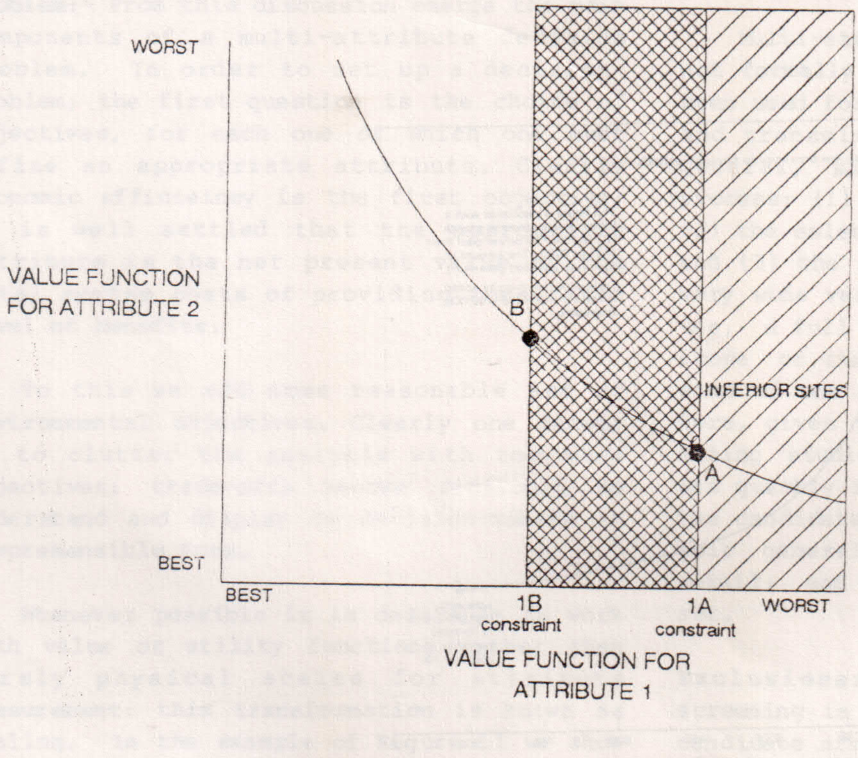

Figure 12: Generation of non-inferior solutions.

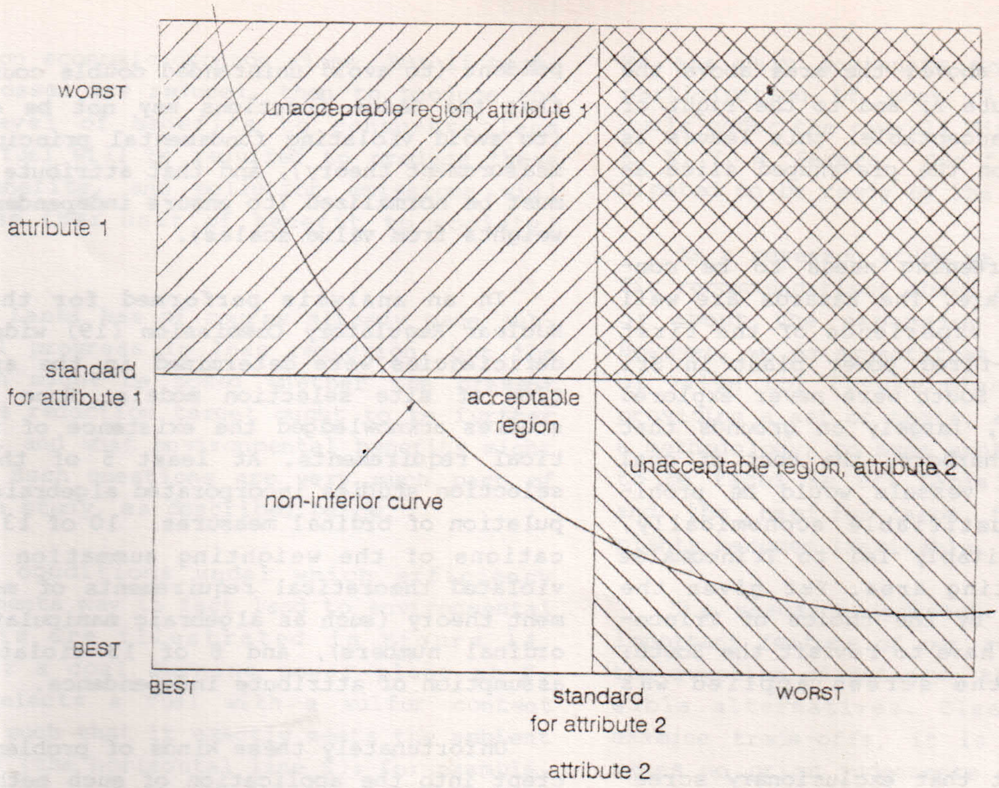

Figure 13: Exclusionary screening

Table 2: 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.

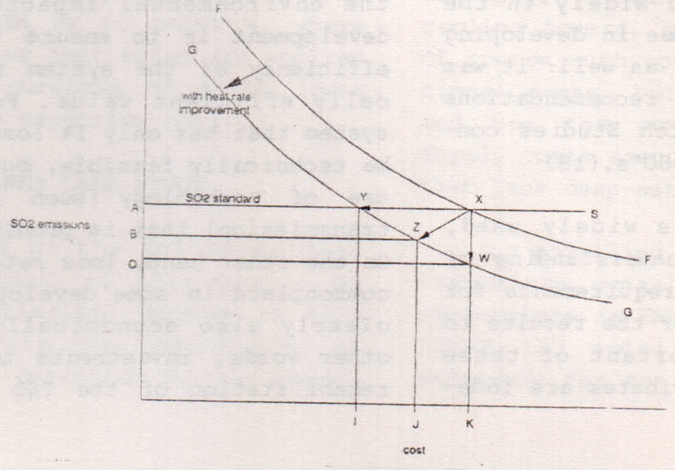

Figure 14: The impact of efficiency improvements

In the example, above, the area above the standard for attribute 1, and to the right of attribute 2, are unacceptable: this leaves as the acceptable region the pie-shaped slice as indicated.

Exclusionary screening needs to be conducted with great care. The hazards 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 would be prohibitive, and not justifiable economically. Such reasoning inevitably led to Trincomalee as the optimal siting area. Yet given the controversy sparked by the choice of Trincomalee, one will now have to revisit the South: in other words, the screen applied was inappropriate.

Indeed, we doubt that exclusionary screening has much value in most developing countries, except for the most obvious requirements: clearly there is no need to examine a 1000Mw coal burning power plant in the Sri Lanka 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 screens with confidence.

The Weighting-Summation Method - 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

$$\sum W_i V_i(X_i)$$

where Wi is the weight, and Vi(Xi) is the value function of attribute Xi.

This procedure, employed widely in the United States, has come into use in developing countries over the past decade as well: it was the basis for site selection recommendations in the various Black and Veatch Studies conducted for Sri Lanka in the 1980's.(18)

Although the approach is widely used, there appears to be little understanding of the existence of 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 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 (19) 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. 10 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.

Unfortunately these kinds of problems have crept into the application of such methods in developing countries as well. Table 2 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 (20). 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).

The point is not that we necessarily disagree with the conclusion. Rather it is that an attempt to present the conclusion as resting upon some scientific process is completely unfounded.

EFFICIENCY IMPROVEMENTS AND THE ENVIRONMENT

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 1% 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: in other words, investments to reduce losses by rehabilitation of the T&D system are justi-

ble on economic grounds alone. But if tech-
al losses are reduced, then to produce the
ne level of benefits to consumers less
sil fuel will be required to produce these
e benefits, and pollution emissions will
crease (per unit of benefit to society)
).

Sri Lanka has of course already made sub-
ntial progress in loss reduction, but the
stion might be posed whether the present
loss reduction target ought to be further
uced, and what environmental benefits might
ult. Such questions are very much part of
case study, as described below.

The conditions under which efficiency
rovements may in fact lead to environmental
nefits are illustrated in Figure 14.
nsider a coal burning power plant at X,
ch selects a fuel with a sulfur content
t is such that it exactly meets the ambient
ndard (the horizontal line S); for example,
order to meet the maximum 24hr standard at
lant with no FGD system, coal with a sulfur
tent no higher than 0.8% might be used.

Efficiency improvements have the general
ect of shifting the non-inferior curve
ard the origin -- from FF, say, to GG. All
er things equal, higher efficiency means
e combination of lower costs and/or lower
ssions: in this case we may suppose that
shift occurs as a result of a heat rate
rovement. With a better heat rate, less
l is required per kwh produced, so fuel
sumption, and SO2 emissions decrease; and
net cost to the utility goes down (fuel
ts less the amortized costs of the invest-
t that produced the heat rate improvement)
say to Z. But now the utility has an
entive to move to Y: by buying cheaper
l, with higher sulfur contents, say 0.9%
there has been a 10% improvement in heat
e) further savings can be achieved without
lating the standard, with the result that
re is no environmental benefit. Of course
m the environmental perspective, the
ired response would be to point W, where
savings from better heat rates are applied
entirely to the purchase of still lower
fur, but also more expensive coal.

THE SRI LANKA CASE STUDY

Substantive work on the Sri Lanka case
dy commenced in April of this year. As
ed earlier, the principal purpose of this
k is to demonstrate the feasibility of
lying the concepts described in this paper.
We are very fortunate to have obtained the participation of many distinguished individuals under the overall direction of Professor K. K. Y. W. Perera. Our final report is anticipated to be ready by the end of the year.

As a research study we will make no specific recommendations about any specific plants, or about the expansion plan of the CEB. However, we do expect that the results will be of value for future planning decisions by providing a set of tools, and a methodology, to make explicit the trade-offs to be faced as Sri Lanka's economy expands, and the need for large fossil-fueled power plants becomes inevitable.

The research approach: Perhaps the most important feature of our research approach is the question of defining the universe of feasible alternatives. Clearly if one is to examine trade-offs, it is important that one makes no prior judgements as to what options should be excluded, and, equally important, that the focus should be on options that are materially different from each other, rather than exhibiting only marginal differences between them. As already noted, most of the environmental work conducted by Black and Veatch focussed on the six sites in Trincomalee Harbor. Yet the six sites differed mainly in physical layout and site development costs, and displayed few environmental trade-offs. All were identically configured pulverized coal plants without FGD systems, and with once-through cooling into the bay.

The result, of course, has been the apparent conclusion that if one wishes to avoid deleterious impacts to the bay ecosystem, a site on the South Coast will be necessary. In fact, however, there is a range of cooling system options that were not considered, including natural and mechanical draft cooling towers, cooling ponds, and long ocean outfalls. All of these would largely avoid the thermal impacts associated with once-though discharge -- although offset, in the case of cooling towers, by increased visual impacts. Of course such options would also incur additional costs, but the question is how much, and how they compare with the higher fuel supply costs associated with South Coast sites that lack deep-water harbors.

The modelling framework: Figure 15 illustrates the overall modelling framework. The centerpiece is ENVIROPLAN, a state-of-the-art LOTUS 123 model assembled by the writer expressly for the analysis of energy-environ-

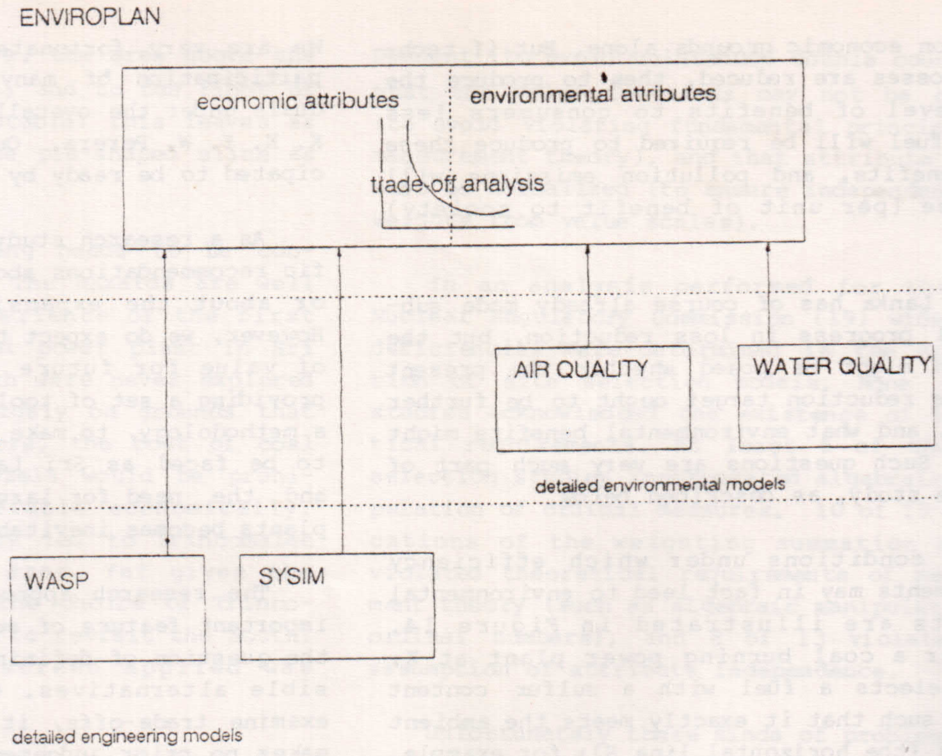

Figure 15: The modelling framework

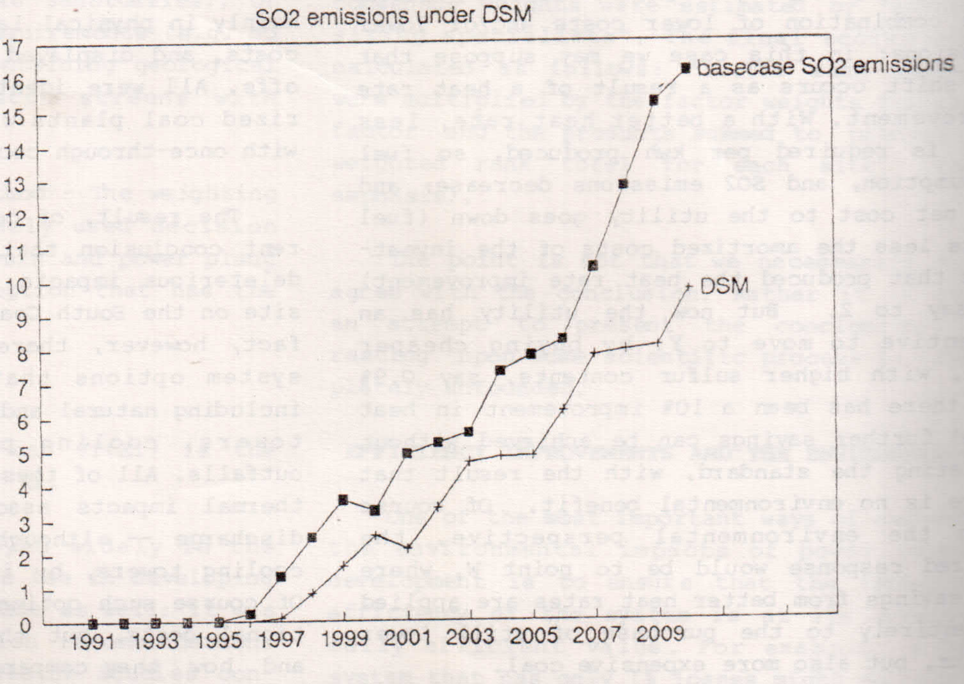

Figure 16: Simulation of the Impacts of Demand Side Management.

mental trade-offs (22). The main requirement 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 is simply unsuited for the sort of sensitivity analysis required here (23). However, ENVIROPLAN is closely calibrated to the WASP results in order to ensure compatibility of our study to the expansion plan alternatives defined by CEB.

One of the important features of ENVIROPLAN is its ability to generate internally consistent scenarios. As an example, consider the option of fitting an FGD system to a proposed coal plant. Relative to the base case technology, this proves to be not merely a matter of increasing the capital and operating costs. In addition there are capacity penalties (because of changed operating conditions, a derating may be required), but also energy penalties (since the FGD system consumes some part of the plant output). Consequently if the net output is to remain the same, the overall plant size has to be increased, or energy must be supplied from other plants.

A second important feature of ENVIROPLAN is its capability to analyze demand side options. On Figure 16, for example, we show the results of a DSM program (that includes a such options as the more widespread use of compact fluorescent lighting fixtures to replace incandescent bulbs), which has the overall effect of lowering the average demand growth rate from 6% to 5%. The impact on SO2 emissions is seen to be quite dramatic.

Attribute scales: As an illustration of the type of attribute scales that are under development, consider the air quality objective. "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. Aside from some of the objections already mentioned, the most serious problem is that the assigned scores were based purely on the "judgement of siting experts", and no rationale for either the choice of scale, or the valuation process is offered (24).

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.

We believe there to be better approaches. In our case study, the air quality impacts of a given site will be captured by the following equation

$$X = \sum_j C_j P_j$$

where X is the cumulative population exposure to the incremental ambient SO2 concentration attributable to the power plant.

Pj is the population in the j-th grid square
Cj is the average annual concentration of SO2 in the j-th square.

The Cj is estimated by application of the standard Gaussian plume model

$$C_j = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(- \frac{y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2} \right)$$

where

u is the mean wind speed (in meters/se
Q is the source term (in g/sec)
H is the stack height (in meters)

The model is implemented in a Lotus 1-2-3 spreadsheet, and is designed for use with very basic 8- or 16-directional windrose data. Stack height, plume rise and source terms are user defined (the source terms are obtained by linkage with the merit order dispatch results from the main Enviroplan spreadsheet). The dispersion coefficients are calculated endogenously according to user-specified stability conditions(25).

This model is of course 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 importance of a population weighting of incremental ambient pollutant concentration is evident from Figure 17, which shows the results of the air quality analysis performed by Black and Veatch for the Trincomalee plant: shown here is the maximum 3-hour SO2 concentration. This of course is a fairly standard calculation for regulatory purposes. The maximum concentrations are seen to lie to the Northwest of the plant yet.

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 from the Southwest, with concentration maxima to 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 environmental impacts and computations designed for regulatory convenience.

SUMMARY AND CONCLUSIONS

In this paper we have presented the outlines of a methodology for incorporating environmental impacts into the power sector planning process. We believe that Multi-attribute decision analysis is a useful approach for quantifying the environmental impacts of power sector development, and for displaying and analyzing the trade-offs that must be made. The approach meets both the fundamental requirements: it is rational, and the process by which including environmental goals affects the outcome is clearly demonstrable.

Although the work on the Sri Lanka case study is still underway, we expect that the results will in fact demonstrate the usefulness of the technique to developing countries. There is little question that continued economic growth and development will require continued expansion of electricity supply even if all of the potential for efficiency improvements are exploited. Moreover, even with extensive utilization of renewable energy sources, a greater reliance on fossil-fueled generation in Sri Lanka is inevitable. It is our hope that our work will contribute to an informed debate on how economic growth and environmental quality objectives must be balanced.

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FOOTNOTES

1. However, it would not 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 discussed these issues. See e.g. M. Chatterji, Editor Energy and Environment in the Developing Countries (New York: John Wiley and Sons, 1981). Moreover, many developing countries began to create environmental institutions in the late 1970s: Sri Lanka's Central Environment Authority was established in 1980.

2. see e.g. Environment and Development: Implementing the World Bank's New Policies Development Committee Paper £17, World bank, Washington, D.C. 1989; or D. Giampaoli Policies and Strategies of the Interamerican Development Bank for the Energy Sector and the Environment Inter-american Development bank, Washington, D.C,, 1988.

3. Indeed, many of the most celebrated instances of unanticipated environmental consequences in developing countries have occurred at major power system projects -- the Akosombo Dam in Ghana, the Aswan Dam in Egypt. However, given the procedures now in place, it is quite unlikely that one would encounter unanticipated impacts on the scale encountered at these projects.

4. For example, the recent USAID report Energy and Environment: An Appraisal of Energy Assistance Strategies for minimizing Environmental Impacts in Developing Countries (Washington, D.C. : United States Agency for International Development, Office of Energy, Oct. 1988) concludes "..In the near term, this calls for devising a strategy that encourages developing countries to assess the costs and benefits of environmental protection -- as well as those of competing alternatives -- at the investment planning stage of energy sector development rather than after project investment decisions have been made."

5. Indeed, we know of no published environmental impact statement that has ever concluded that a project should not go forward.

6. As one reviews the 20 year history of the EIS process in the United States the extent to which it has affected the substance of environmental objectives remains unclear. In almost every case, EISs for large new power plants were prepared after the siting decision had been made, and represented nothing more than ex post justifications of decisions already made on other grounds. Small wonder then that despite the existence of EISs that alleged no significant environmental impacts, so many utility projects were delayed or brought to a halt.

7. 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.

8. Black and Veatch, Trincomalee Thermal Power Project, Site Evaluation and Selection Study, Phase II, Final Report, September 1985.

9. Black and Veatch International Thermal Generation Options Study, October 1988.

10. 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.

11. It should be noted that SO2 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. SO2 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), December 1989.

12. 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, D.C. 1988.

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

4. This discussion is based on B. Hobbs Ana- ytical Multi-objective Decision Methods for ower Plant Siting (Nuclear Regulatory ommission, NUREG/CR-1687, August 1979), which s the most comprehensive presentation of ifferent multi-attribute decision analysis ethods as they apply to power sector problems and siting decisions in particular).

5. We follow here the discussion of P. Meier nd L. Ruff The Spatial Dimension of Regula- ory Cost Impact Assessment (National Commis- ion on Air Quality, 1979).

6. For detailed discussion, see J. Cohon and . Marks A Review and Evaluation of Multi- bjective programming techniques Water esources Research, 11,2, p. 208-220, 1975.

7. It is hard to evaluate whether cases in hich formal models were used for siting deci- ions were any better than in cases in which hey were not. It is certainly true that the ost celebrated siting controversies in the nited States, from the Storm King Mountain umped storage project to the Shoreham and eabrook nuclear plants, would not have been esolved sooner, or at less cost to the conomy, had formal siting models been pplied. But these siting decisions were in act made in the 1960's, and the use of formal iting models developed in the 1970's as a irect consequence of the problems encountered t these (and other) plants. The most impor- ant lesson from the application of formal ting models in the United States is the need r public participation in the decision pro- ess: it was very quickly realized that as ecision 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.

18. 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).

19. see M. Rowe et al. An Assessment of Nuclear Power Plant Siting Methods Report NUREG/CR-1689, U.S. Nuclear regulatory Commission, Washington, D.C., 1979.

20. 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 this Report.

21. It should be noted that this reasoning applies only to the reduction of technical losses: 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 impact on the utility, and on the price elasticity of demand of those consumers would then pay the going tariff. 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. On balance one suspects that these effects 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.

22. ENVIROPLAN: A Software Package for Multi-attribute Energy-Environmental Simulation of Developing Country Power Systems. Washington, D.C., July 1991.

23. 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 requirements of our case study.

24. Again this is not necessarily intended as a criticism of the study: as noted by Black and Veatch, the method applied is widely used in the United States. However, as noted earlier, the claim that the method is justifiable because it is widely used is not reassuring.

25. One of the areas where we believe the Trincomalee Air quality analysis to have been unfairly criticized is in the use of meteorological data from Guam. In fact we judge this to have been a perfectly reasonable step. There is surely no regulatory entity in the world that has conducted more air quality modelling than the U.S. Nuclear Regulatory Commission. In its Guidelines for Regulatory Analysis it is stated 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" The point is simply that for the purpose of impact calculations, great precision in meteorology proves not to be very important.

Figure 17: Maximum 3-hr SO_2 concentrations