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# Environmental Costs and Power Systems Planning

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## I. INTRODUCTION

This paper reviews the methods used in power systems planning in selected countries, with particular reference to the treatment of environmental costs. In doing so it looks at both the analytical models employed, as well as the decision-making framework within which they are embedded. The aim of the exercise is to evaluate the suitability of these models and methods for power systems planning in developing countries. Some of them are already in use in these countries and others are not. There are issues of data availability, computing requirements and geographical relevance that might limit the usefulness of some of the models. On the other hand there is a pressing need to take systematic account of environmental factors in energy planning in developing countries, and the current procedures are, in many cases, inadequate. Hence it is important to see where, and how, they might be strengthened.

The paper proceeds as follows. In Section II a range of models used in power systems and energy planning are surveyed. Of particular interest in the context of this report is their treatment of environmental issues (in the broadest sense) and their operational requirements (both in terms of computing and personnel). In Section III the role of these models is surveyed in a wider decision-making context, by looking at the other stages in the decision-making process and by examining how decisions are actually made on energy investment in France, Germany, Sweden, the UK and the US. Formal systems modelling is never more than a guide to the sorts of options that are available and it is interesting to see how environmental issues, which may get little or no consideration at the systems level, are in fact incorporated in the decision-making process. In Section IV, the relevance of these models, and associated decision-making processes, for developing countries is evaluated. Section V concludes the report with some recommendations on how one might strengthen the planning capability of power utilities in developing countries. There are two annexes to the paper. Annex 1 lists the people who have been consulted in connection with the preparation of the paper and Annex 2 the documents that have been referred to.

Two preliminary remarks should be made at this stage. The first is that, in surveying the models for systems planning, attention has not been focussed solely on the power systems planning models. Partly this is because there are several interesting environmental-energy models that deal with the power sector and partly because environmental issues are probably better addressed in the context of a broader energy model anyway. The second is that many of the documents referred to in this paper are not published, or not readily available. Wherever possible, the contact address has been given so that they can be obtained by writing to the authors directly.

## II A SURVEY OF MODELS FOR POWER SYSTEMS PLANNING THAT INCORPORATE ENVIRONMENTAL CONSIDERATIONS

Environmental costs arise in a number of ways when power is generated. Table 1 summarises the environmental impacts of the main sources of electricity: oil, gas, coal, hydropower and nuclear power. The impacts work through their effects on air, water, land and soils, wildlife, noise, visual beauty and physical safety. In addition to the direct impacts listed in the Table, there are:

(a) the environmental effects of extraction to be taken into account for the fossil fuels (where these are extracted domestically). Such effects include factors such as mine liquid waste disposal, land subsidence, and the accidents, noise and dust pollution associated with mining.

(b) the environmental effects of transmission and distribution. These include visual and aesthetic effects, as well as land use issues.

Having identified the environmental impacts, the next task would be to value them. Such values include damage to property and productive capacity, as well as the loss and pain and suffering felt by human beings as a result of the deterioration of the environment. In principle, <u>all these impacts can be quantified in monetary terms</u>, and a great deal has been done, both theoretically and empirically on the valuation of these effects in developed countries[1]. If values could be established for the environmental effects, they should be included as costs of the particular power source, <u>and any decision on which type of plants are to be built to meet a given demand should be based on the minimisation of all the costs, including environmental costs</u>. Conversely, ignoring these costs will result in too much being invested in this sector, as private returns will be below social returns.

Although it is possible to value these costs in principle, this is rarely done in practice, especially at the <u>early project screening stage</u>, which is what the power systems planning exercise constitutes. Of over 30 systems models surveyed, only two purported to include the environmental damage costs in the objective function. These were: (a) an energy appraisal model developed at the Rensselaer Polytechnic Institute (the RPI model) and a model developed by Decision Focus Inc. for EPRI with the objective of studying costs and benefits of over/under

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[1] For details see D.W. Pearce and A. Markandya <u>Environmental Policy Benefits: Monetary Valuation</u>, OECD, Paris, 1989, and D.W. Pearce (ed.) <u>Benefits Estimates and Environmental Decision-Making</u>, Earthscan, London, 1990.

TABLE 1

ENVIRONMENTAL IMPACTS OF ENERGY DEVELOPMENT

| ENERGY SOURCES | AIR | WATER (surface, underground/inland and marine) | LAND AND SOILS | WILD LIFE | OTHERS: Solid waste, risks, human health, noise, visual... |
|---|---|---|---|---|---|
| URANIUM FUEL CYCLE AND ELECTRICITY FROM NUCLEAR POWER PLANTS | -Radioactive dust<br>-Gaseous effluent (radionuclides, F, NO2)<br>-Noble gas H.3, I.131, C.14<br>-Local climatic impact of cooling towers | -Mine drainage<br>-Underground water contamination<br>-Water availability<br>-Thermal releases<br>-Liquid radionuclide emission (H.3, Co.60, Sr.90, I.131, Ru.106, Cs.136 and 137) | -Land subsidence (mine)<br>-Land reclamation of open cast mines<br>-Land use for mines (applicable where mining takes place domestically) | -Secondary effects of impacts on water, land and air | -Radioactive products<br>-Mine water<br>-Mill tailing water (toxic metal liquid and solid chemical wastes, radiological wastes)<br>-Recycled fision products<br>-High level radioactive wastes<br>-Visual impact of cooling towers and power lines<br>-Noise<br>-Occupational risks |
| | -Decontamination and decommissioning of nuclear power plants | | | | |
| HYDROPOWER | -Micro-climatic effects | -Effect on hydrological cycles<br>-Water quality and resources | -Land irreversibly flooded<br>-Landslide risks | -Wildlife habitat of rivers<br>-change in ecosystems<br>-Fish migration affected | -Visual impacts<br>-Risks of dam rupture<br>-Health effects<br>-Resettlement issues |
| OTHERS: Biomass, geothermal wind and solar energies | -Biomass combustion:air pollution, particulates<br>-Geothermal:air pollution | -Biomass conversion: water pollution, water availability<br>-Geothermal:water pollution | -Land use for energy plantations<br>-Land requirement of solar energy | -Biomass: ecosystem disruption by energy plantations | -Noise of wind generators<br>-Visual impact of wind generators<br>-Biomass risk to workers<br>-Photovoltaic toxic pollution when decommissioning |
| ELECTRICITY GENERATION FROM FOSSIL FUELS (excluding nuclear power) | -SO2, NO2, CO, CO2, HC, trace elements, particulates, radionuclides<br>-Long-range transport and decomposition of pollutants<br>-Climatic impacts of cooling towers | -Water availablity<br>-Thermal releases | -Land requirement | -Secondary effects on water, air and land | -Visual impact of cooling towers and power lines<br>-Solid wastes<br>-Ash disposal<br>-Noise |

Source: OECD (1986), The State of the Environment, 1985, OECD, Paris.

capacity in power systems planning. However, for neither of these are there any significant applications available and, as far as can be ascertained, neither of them have been applied in developing countries. A recent survey of energy-environment models quotes: "In some models [environmental costs] are included in the objective function, but this kind of optimisation can be carried out only in a very rough level, because the economic consequences of the environmental effects cannot be adequately defined [in monetary terms]"[2]. In view of this, no further consideration is given to the treatment of environmental impacts in power systems planning through the measurement of the value of the environmental damage.

The other models concerned with power or energy systems planning vary in their treatment of environmental issues. The four approaches used are:

(a) to include the costs of environmental protection as part of the costs of energy supply and to minimise the total costs;

(b) to do (a) above but to carry out the minimisation subject to certain environmental constraints;

(c) to carry out the minimisation (as in (a) above) and then calculate the environmental impacts in a separate module. The model can then be run several times to see how the 'solution' varies if certain restrictions are imposed, such as 'no further development of coal' or 'at least 20% of power must come from nuclear sources';

(d) not to carry out any optimisation at all, but to see what the implications of alternative power development strategies are. This is close to (c) above, but does not include the cost minimisation routine.

A list of the main models available is given in Tables 2 and 3[3]. Table 2 lists all energy supply models, and Table 3 all integrated energy models, which include both demand and supply side effects. Before discussing these in more detail there are

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[2] See UNEP, The Environmental Impacts of Production and Use of Energy, Part IV, Phase III, Technical Research Centre of Finland, ESPOO, 1986.

[3] Tables 2 and 3 do not cover all the energy supply planning models in existence. The basic structure of the models is so familiar that several others along the same lines exist. However, the list probably includes all of the main ones which have an environmental module and for which information on applications, particularly in developing countries, is available.

TABLE 2

ENERGY SUPPLY MODELS

| No. | Name of Model | Time | Modelling Technique | Applications | Computer Requirements | Environmental Constraints | Other Comments |
|---|---|---|---|---|---|---|---|
| 1 | Energy Flow Optimisation Model (EFOM) | medium to long term | optimisation (linear program) or simulation | -Europe (EC) -Thailand -Swaziland -Turkey -Yugoslavia | IBM 3033 ICL 2960 | Has been used for evaluating costs of alt. air emissions standards | Uses Commercial Packages Joint EC model Germany/France |
| 2 | Energy Planning System Model (Bogazici) | medium term (15 years horizon) (3 year steps) | optimisation (linear program) decisions after each step | -Turkey | not known | not explicitly addressed | only applied to Turkey |
| 3 | Energy Technology Asessment Model (Stanford) | long term | optimisation (non-linear programming) | -Mexico | not known | not explicitly addressed | |
| 4 | KWU and INTERATOM Models (Germany) | medium term long term | | -OPEC countries -Indonesia | memory>50Kb. program language Fortran | not addressed | very country specific, focussing on oil flows |
| 5 | Energy System Network Brookhaven National Lab. (BNL) | short term-three years long term version as well | accounting - network flow | -Egypt -Thailand | not known | addressed in constraint form in the REFS version | Used to allocate capacity to counties based on env. impacts |
| 6 | Market Allocation - MARKAL | medium to long term | linear programming optimization | -Brazil -Guandong China -Korea -Indonesia -Morocco -OECD countries | program language Omni. Main frame and micro versions exist | deals with CO2 emissions | developed by IEA to analyse impacts of CO2 emissions controls on the energy sector |
| 7 | Model for Energy Supply Strategy Alternatives & their General Environ. Impact (MESSAGE) | medium to long term | dynamic linear programming | -FRG, Austria Some initial work in: -China -Iran -Nigeria | main frame and micro versions exist | air emissions constraints explicitly addressed | developed in Germany. Still being improved |
| 8 | RETINE | medium to long term | static optimization with linear constraints and non-linear objective function | -Ecuador -China | main frame and micro versions exist | not explicitly addressed | Swiss developed model |
| 9 | Wein Automatic System Planning Package (WASP) | medium to long term | dynamic optimization with probabilistic simulation | applied in more than 40 countries | memory>64Kb. IBM AT, PC versions & main frame | not explicitly addressed but can be run with an impacts module | widely used for power systems planning. Experience with impacts module not positive |
| 10 | Argonne Utility Simulation Model (ARGUS) | medium to long term | one period non-linear optimization | USA | program language Fortran can be run on micro computers | deals specifically with coal | sophisticated model to minise costs of meeting air pollution stds. for coal |

TABLE 2

ENERGY SUPPLY MODELS

| No. | Name of Model | Time | Modelling Technique | Applications | Computer Requirements | Environmental Constraints | Other Comments |
|---|---|---|---|---|---|---|---|
| 11 | SPSEK | medium to long term | dynamic linear optimization but not with respect to environmental constraints | Poland | not known | emissions of air pollutants are calculated | still being developed |
| 12 | WAGP | medium to long term | combines screening and branch and bound logics to select optimum capacity expansion plan | applications outside the US not known | details not known | explicitly addressed in constraint form | developed by Westinghouse |
| 13 | Electric Generation Expansion Analysis System (EGEAS) | medium to long term | solution methods: screening curves, linear & dynamic, programming, generised benders decomp. analysis. | applications outside the US not known | details not known | explicitly addressed in constraint form. Some impacts also reported | sophisticated model developed by EPRI |

Source: Voss et al. (1989), UNEP (1986) and author's survey.

Table 3

Integrated Energy Models

| No. | Name of Model | Time | Modelling Technique | Application | Computer Requirements | Environmental Constraints | Other Comments |
|---|---|---|---|---|---|---|---|
| 1 | ENERPLAN Energy Planning Model | short term medium term long term | set of integrated simulation models -energy balance -statistics -simulation model -traditional sector resource model | -Thailand -Costa Rica | Memory >256 kB Program language BASIC Implementations IBM-PC NEC | Not addressed | Developed by the Tokyo Energy Research Group |
| 2 | ENVEST | short term medium term | set of interlinked simulated and optimi -zation models: ('bottoms up' approach) | -Morocco -Costa Rica | Memory >256 kB Operating system MS-DOS. Program language BASIC Implementations IBM-PC NEC | Not addressed | No further details available |
| 3 | IDEA | short term medium term long term | set of interlinked simulated and optimi -sation models: -subsectoral -energy sector -macro-economic analysis | -Sri Lanka -Indonesia -Haiti -Dominican Republic | Memory >320 kB Operating system MS-DOS Implementations IBM-PC | Not addressed | Developed in Argentina. Not many details available |
| 4 | LEAP Long Range Energy Alternative Planning Systems | medium term long term | set of interlinked simulated models: -macro-economic -demand -supply (transfer) -resource model | -Kenya(planned) (Earlier version without environmental module has been used in several LDCs) | Memory >256 kB Operating system MS-DOS Implementations IBM-PC | Environmental data base is being added to the new version to be released in early 1990 | Developed at Energy Systems Research Group Boston. Uses spreadsheet framework |
| 5 | MESAP Microcomputer Based Energy Sector Analysis and Planning System | short term medium term long term | integrated set of simulated account and optimisation, models: demand, supply (opt.), energy balance, statistics, invest -ment calculations | -Algeria -Iran | Memory >1000 kB Operating system MS-DOS Implementations IBM-PC | Environmental issues are treated as in MESSAGE, which is one module in MESAP. See Table 2 | Developed at IKE, Stuttgart. Compares results from more than one model - e.g. WASP and MESSAGE |
| 6 | ENPEP Energy & Power Evaluation Program | medium term long term | integrated set of models: macro, demand, balance of demand and supply, load forecast, impacts | ENPEP is yet in a developing stage - initial trials have been carried out on data from Jamaica | Memory >640 kB Operating system MS-DOS. Program language FORTRAN Implementations IBM-PC, AT IEC | IMPACTS module is being extensively revised. Geographical dispersion of pollution is being added | Developed at Argonne. Electric Supply Model based on Wasp is linked to demand and IMPACTS modules See Table 2 |
| 7 | Swedish Integrated Electricity Planning Model | short term medium term long term | integrated set of models: macro, demand, power demand, electricity conservation, supply optimisation. Uses a scenario approach | Sweden | Not known | Environmental issues not explicitly addressed but 'environmental' supply scenario is examined | Developed at Vattenfall and Lund University Model is discussed further in the text |

Source: Voss et al. (1989) and author's survey some points of terminology to note. Models that do not include any optimization with respect to the environmental constraints are referred to as simulation models. In Table 2 there are the WASP and SPSEK models and in Table 3 there are the ENERPLAN, and LEAP models. Models that take account of the environmental constraints explicitly (case (b) above) are referred to as integrated environment-energy models whereas those that look at the impacts of the optimization on the environment (case (c) above) are referred to as appended environment-energy models[4]. Integrated energy-environment models include ARGUS, EFOM, MARKAL and MESSAGE, WAGP and EGEAS (Table 2) and IDEA and MESAP (Table 3). Models that append an environmental module giving the impacts of the energy expansion plan include WASP and SPSEK.

In principle all supply models could include environmental protection costs. If such costs are included in the cost minimization exercise then at least some attention has been paid to the social costs of energy supply. The problem with this approach is that it biases choices against those projects in which the mitigation costs can be assessed, and where there are some technologies for mitigation available. For example, technologies for reducing emissions of $SO_2$ and $NO_x$ are well known and a power authority could be required to adopt the 'best practicable technology' with regard to these. However, the environmental costs of hydropower development are less easily identified and therefore less easily mitigated. A cost minimization exercise which included the costs of air pollution control but not the social costs of hydropower development would clearly be biased against fossil fuels in an undesirable way[5].

Given such a large of models, it is necessary to recognize that they do not all serve the same purpose. A model such as ARGUS specialises in the optimization of coal power plants, in the general context of a power sector model, whereas a model such as MESAP looks at the very broad issues of energy supply development in the context of a national, or regional, balance of supply and demand. The two could easily complement each other in any energy planning exercise and so it is important to recognize that more

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[4] This terminology is taken from T.D. Wolsko et al. An Integrated Energy Planning Model: Interface Between Energy Planning and Environmental Impacts, Argonne National Laboratory, Illinois, 1987.

[5] Discussions with several power planners in the World Bank, for example, has revealed that whereas pollution mitigation costs for fossil fuel plants are generally included in the WASP runs (in accordance with local standards) the same does not happen for hydro plants, where costs of monitoring and mitigating the impacts are less clear at the planning stage.

than one model may, and probably should, be used to analyse the environmental impacts of a particular energy supply plan.

Nevertheless, there is a considerable overlap between the models and it would be useful to have a systematic comparative survey of them. Unfortunately no such survey exists, although there are occasional studies looking at the relative performance of some of the models. These are reported below, along with the key features of the models themselves.

## Energy Supply Models

### Integrated Environment-Energy Models

The integrated environment-energy models are concerned with the minimisation of the cost of achieving a given increase in energy supply, subject to a number of constraints. These include technological constraints on the transformation of energy from one form to another, physical constraints on how fast new energy sources can be developed, financial constraints on the expenditures that can be undertaken in any given period and environmental constraints on the permitted emissions from any plant, or in any geographically defined area. Because they do not take explicit account of the value of the environmental damage done, the analytical method is not one of net benefit maximisation but of cost effectiveness. This term is frequently used to describe such models.

Of the six models in this category (EFOM, MARKAL, MESSAGE ARGUS, WAGP and EGEAS), the first three use a linear optimisation technique, which involves the minimisation of the discounted cost of meeting a given increase in demand for energy, subject to a large number of intertemporal constraints. The fourth uses a static non-linear optimisation routine and the fifth and sixth use a multiplicity of techniques.

The fourth model (ARGUS) is specifically concerned with the coal sector. Operated on a power pool basis, it optimises the supply expansion programme, taking account of the options of repowering old units, building new ones and dispatching power optimally to meet the environmental constraints. Because the power sector is a major user of coal and its use can affect the market price of coal, the model allows for feedback between its implied demand for different types of coal and the price of coal. The optimisation, however, is done on a one period basis and is not dynamic. Also, since the programme has not been widely used and does not have a proven track record it was important to test it against other models such as WASP. Such tests have been carried out for a number of power pools in the US[6]. In terms of cumulative capacity added, the results are very similar (a difference of 2-3%). Furthermore, where significant differences in results do arise (e.g. over capacity additions by technology) these can be explained in terms of the differences in the constraints or the input assumptions used.

A similar test has been carried out by IKE in Germany, comparing their MESSAGE model with WASP. The case study was carried out on Jordanian data and again the power plant solutions were found to be very similar when environmental constraints were excluded[7]. Thus, although it is not completely clear, the evidence seems to suggest that these 'new' models do not deviate significantly in terms of their general power expansion characteristics from the better established models such as WASP.

As far as the treatment of environmental issues is concerned, the models have something to offer, but the results have to be interpreted with care. Most importantly, it has to be recognised that the constraints are only applied to the air pollution issue. No such constraints appear for water quality, health effects, loss of biodiversity or risks of accidents, all of which can be important impacts of energy, particularly power, development. Not including such features as constraints on the optimisation may not be serious, if there are no trade-offs with regard to the impact in question, and if the costs of meeting a given standard are included in the costs of developing that option. For example, consider the development of a river basin for power. One environmental impact is the water quality. This can be met by: a combination of: (a) clearing the impounded area of a given amount of vegetation, (b) induced aeration at the point of water release, and (c) adjusting the release of water to ensure that water quality standards are met. If the water quality constraint is included in the optimisation, the decision on the design and selection of the hydropower plant may be different, and superior, to what it would be if a particular policy were chosen in advance and its costs included as part of the cost of hydropower development. However, if the choice of that environmental control option is made with care and its costs included in full, including any monitoring costs, then the error should not be too large. So far, this has not been established empirically. It would be interesting to see the differences in choice of technology that would emerge for each approach.

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[6] See K.A. Guziel, T. Veselka and K. Rose, Results of the Model Comparison Study: WASP Versus ARGUS, Argonne National Laboratory, Illinois, 1989.

[7] Details may be obtained from Dr. A. Reuter, Institut fur Kernenergetik und Energiesysteme, University of Stuttgart, Germany.

Subject to this proviso, the models can be used to answer several useful questions. The most obvious one is, how do the total costs of meeting a given set of air quality standards vary as the standard itself varies. EFOM and MARKAL have been used to answer such questions with respect to $CO_2$, and ARGUS, EFOM and MESSAGE with respect to other air emissions[8].

Other questions that can be addressed are:

(a) what impact would geographically determined emission constraints, as opposed to plant level constraints have on the optimal solution?

(b) how would the introduction of sulphur or carbon taxes alter the solution, or conversely, what taxes would be needed to bring about a given solution where individual agents made investment and supply decisions?

(c) is there any scope for emissions trading, or bubbling?

(d) can the constraints be formulated in terms of depositions rather than emissions, and what differences result?

As far as the power sector is concerned, ARGUS has been used specifically to answer these questions. To reform the constraints in terms of deposition limits, the model has been used in conjunction with the ASTRAP model and the results have been interesting.

Appended Environment-Energy Models

Of the models listed in Table 2, the WASP and SPSEK models generate a set of environmental impacts. These can then be used

[8] See H.D. Haasis et al. , Energy and Environment: Optimal Control Strategies for Reducing Emissions from Energy Conversion and Use, RISO National Laboratory, Roskilde, Denmark, 1989; A. Voss and G. Schmid, Cost Effectiveness Analysis: The Key for the Identification of Efficient Response Strategies to the Climate Issue, Proceedings of an Experts' Seminar, International Panel on Climate Change, IEA, Paris, 1989; T.D. Veselka et al., An Analysis of the Sirkoski Bill, H.R. 4567, to Control Acid Rain, ANL/EES-TM-338, 1987; D.G Streets et al. Controlling Acidic Deposition: Targeted Strategies for Reducing Sulfur Dioxide Emissions, ANL/EES-TM-282, 1984; D.B. Garvey et al., The "Control-or-Retire" Strategy for Reducing Sulfur Dioxide Emissions from Power Plants, ANL/EES-TM-283, 1984. The last three are technical papers from Argonne National Laboratory, Illinois. Finally, see D.G. Streets and T.D. Veselka, Economic Incentives for the Reduction of Sulfur Dioxide Emissions, Energy Systems and Policy, 11, 39-59, 1987.

to (a) identify the additional environmental mitigation expenditures that need to be incurred and to include those expenditures in a rerun of the optimisation model, and (b) investigate the implications of alternative supply scenarios in terms of their environmental impacts.

The WASP model was expanded to include an IMPACTS module a few years ago and has been extensively described elsewhere[9]. In practice, however, it has not proved easy to apply, or particularly useful. None of the several World Bank staff involved in the power sector used it. Indications are that it is too crude, the presentation difficult to follow and that its results can be improved upon by taking account of factors specific to the country in question. Some work along the last lines is taking place in Turkey, but no results have been made available as yet. The team at Argonne, who designed the IMPACTS module have been aware of its shortcomings, and have been working on producing a revised version that should be available shortly.

In principle, these impacts modules are useful tools of analysis. In particular they can be used to check on the reasonableness of the optimisation models referred to above, and to actually show what the environmental effects would be of a particular expansion plan. It is important, however, for the impacts to be presented in a detailed enough form to be relevant to the situation being analysed, and it is not clear whether a 'generic' model can provide enough useful detail in this sense.

Integrated Energy Models

The models described above look only at the supply side of the energy issue. They take demand as given and do not investigate the impacts of using prices and other instruments of energy demand management to bring demand and supply into balance. From an environmental perspective this could be an important omission, because energy conservation measures are generally benign with respect to the environment. Furthermore, there is considerable evidence to suggest that substantial efficiency gains can be made in developing countries at relatively low cost compared to the costs of increased energy supply[10].

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[9] See, T.D. Wolsko et al. (op. cit.), 1987, and the associated WASP manual (IMPACTS Chapter).

[10] See End-Use Electricity Conservation: Options for Developing Countries, Energy Department Paper No. 32, World Bank Energy Department, 1986.

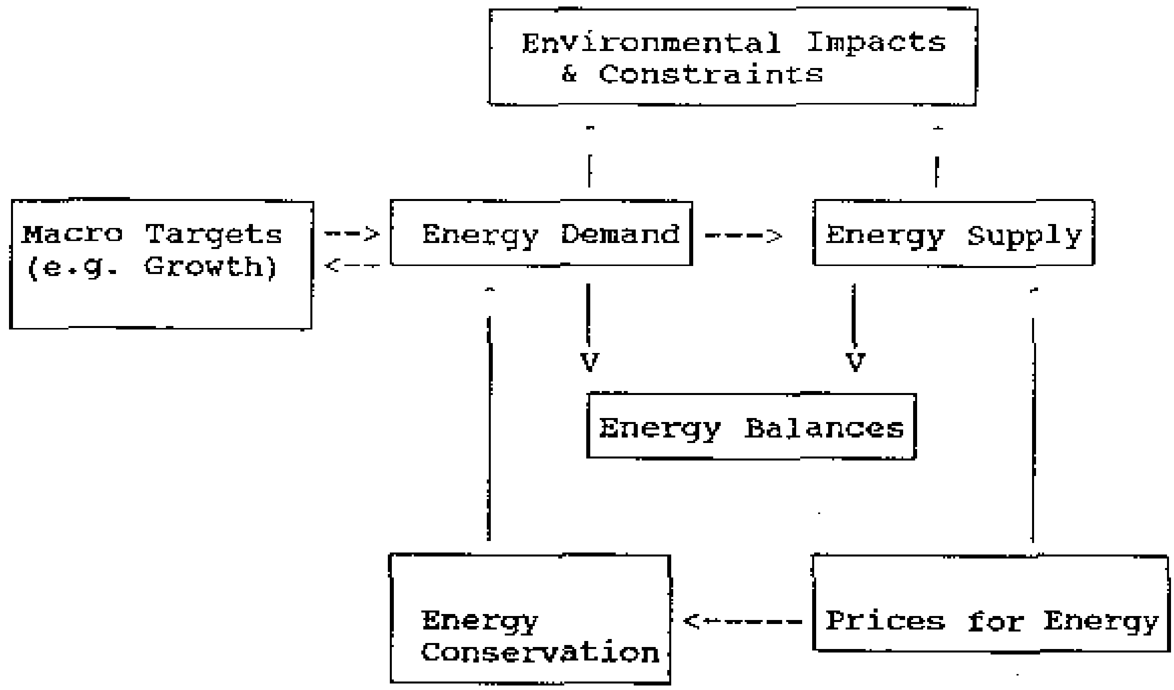


Figure 1: Methodology for an Integrated Energy Model

Of the integrated models listed in Table 3, only the MESAP, LEAP and ENPEP explicitly allow for environmental constraints. However, no results of their applications with the environmental modules in situ have as yet been published. Hence it is not clear to what extent they follow the schematic methodology outlined in Figure 1. One application, which does not have an explicit environmental dimension, but which does look at the feedback between energy demand, supply and conservation in the context of environmental issues is the Swedish Model. The results of this are quite revealing and are discussed below.

Results of an Integrated Swedish Energy Model

In a recent paper on electricity planning in Sweden, the authors examine four demand and three supply scenarios, all of which, they claim, are consistent with the macroeconomic objective of achieving 1.9% real GNP growth to the year 2010. The scenarios are as follows:

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Demand:
- (i) a reference scenario, based on current demand forecasts and no new policy measures;
- (ii) an efficiency scenario, based on high penetration of efficient end use technologies that are commercially available and cost effective;
- (iii) a high efficiency scenario, based, in addition, on selected technologies that are currently in advanced stages of development; and
- (iv) an advanced technology scenario that includes, in addition, some measures that are still in the research and development stage.

Supply:
- (i) an economic dispatch scenario, based on the traditional notion of constructing new power plants in order of increasing cost;
- (ii) a natural gas/biomass scenario, which excludes the use of coal based technologies, but brings in currently underutilised forest residue resources and wind; and
- (iii) an environmental dispatch scenario, that specifies new power plants in order of increasing net carbon emissions per unit of electricity supplied.

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11 B. Bodlund et al. The Challenge of Choices: Technology Options for the Swedish Electricity Sector, in 'Electricity: Efficient End-Use and New Generation Technologies, and their Planning Implications' (eds. T.B. Johansson, B. Bodlund and R.H. Williams), Lund University Press, Lund, Sweden, 1989.

All calculations assume that current restrictions on nuclear and hydro power development apply. The results are summarised in Table 4. In each case the same electricity energy services are supplied, but generation is 21% lower in the efficiency scenario and 37% lower in the high efficiency scenario. There are clearly environmental benefits to this but, even ignoring these, the costs of supplying the energy services are 12% lower in the efficiency case and 19% lower in the high efficiency case. As far as the dispatch scenarios are concerned the costs are up to 4% higher for the natural gas scenario, and up to 12% higher for the environmental scenario. Whether these higher costs are justified can only be determined by looking at the environmental impacts of the alternative scenarios and valuing the environmental damage under each one.

One may wish to question many of the assumptions underlying this analysis, such as the costs of cost efficient technologies and the assumption that growth would be unaffected by switching between them, but the methodology is undoubtedly interesting and shows the kinds of uses to which integrated simulation models can be put.

TABLE 4

PREDICTED TOTAL ANNUALISED COSTS FOR ELECTRICITY IN SWEDEN
(Cents per Kwh. Equivalent)

| Demand----> ↓ Supply Scenario | Reference Scenario | Efficiency Scenario | High Efficiency Scenario |
|---|---|---|---|
| Economic Dispatch | 2.6 | 2.3 | 2.1 |
| Natural Gas Dispatch | 2.7 | 2.4 | 2.3 |
| Environmental Dispatch | 2.9 | 2.6 | 2.3 |
| Electricity Generated (TWh equivalent) | 194 | 111 | 96 |

All figures include costs of generating capacity, efficient end use technology and fuel switching. Costs are annualised using a 6% real discount rate. Current (1987) estimated annualised costs of electricity in Sweden are 2.8 cents/Kwh equivalent.

Source: Bodlund et al (op. cit.)

## III POWER INVESTMENT CHOICES AND ENVIRONMENTAL CONSIDERATIONS: DECISION-MAKING AIDS AND EVIDENCE FROM SELECTED COUNTRIES

In the decision-making process for power investments, the systems planning exercise is, of course, only a part. Where the decision is taken in the public sector it will reflect, in addition to the economic costs, wider considerations such as security and national self-sufficiency, risk of interruptions and accidents and the macroeconomic needs of particular regions of the country; Where the decision is taken by the private sector, issues of cash flow, pay back period, and uncertainty of future costs and revenues will play a major part.

For both private and public sector power planning in most developed countries, and many developing ones, one can distinguish a number of stages in the process. The first is the identification of the candidate plants. At this stage some attention may be paid to environmental factors from a technological point of view but they are not likely to be the most important consideration. In fact, it is often at this point that strategic and other factors play a major part, by eliminating certain options and including others. The second stage involves a systems planning exercise along the lines defined in the last section. Here, it is possible to bring in environmental costs in various ways, and these have been discussed at length above. Once the projects have been 'selected' in principle, they undergo various levels of appraisal. These include cost benefit analysis, but may also involve risk analysis and multi-criteria analysis. At this stage, the environmental issues are examined in greater detail. Most countries now mandate an environmental impact analysis and some attempt to compare the environmental costs of the individual plants with their 'best' alternatives. Thus, for example, in the United Kingdom, during the Sizewell B inquiry, there was a considerable amount of effort devoted to measuring the relative environmental costs of nuclear versus coal power plants. This calculus was regarded as being important independently of the relative overall net benefits of each of the plants[12].

Risk analysis has been used particularly in connection with the design of nuclear plants. The 1988 World Energy Conference reports on the use of the ALARA principle[13] (as low as reasonably

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12 See T. O'Riordan et al., Sizewell B: An Anatomy of the Inquiry, Macmillan Press, London, 1988.

13 See Report: Environmental Effects Arising from Electricity Supply and Utilization and the Resulting Costs to the Utility, World Energy Conference, London. For a clear and useful exposition of risk analysis see B. Fishoff, Acceptable Risk,

achievable) in determining whether a particular process of emission control is justified. It is based on a quantitative relationship between reduced risk and the additional expenditure required to achieve that reduction. The chosen level is then determined by either making a judgment on what is reasonable or conducting a benefit cost analysis using benefit estimates of the reduced risk. It is noteworthy, however, that such techniques are not generally used for other types of power investments.

The multicriteria approach has been applied in a number of cases to the energy environment trade-off[14]. Essentially the method identifies a number of attributes of a project or plan (such as overall cost, risk of accident, numbers of people displaced, environmental impacts etc.) that are of interest and evaluates it by calculating a weighted average (additive or multiplicative) of the actual values of the attributes. Clearly the issue is how the weights should be determined. A number of suggestions exist, such as using a questionnaire approach on the decision-makers to determine their preferences, looking at the decisions they have made in the past etc. None of these is really satisfactory, although Merill (1989) argues that just looking carefully at the values of the attributes in a multi-dimensional sense helps to eliminate a large number of options. The remaining options can then be traded-off more formally.

The decision-makers use information from all these analyses and then add their own political dimension for public sector projects or their business judgment in the case of private sector projects. In the remainder of this section, the actual process by which decisions are made is reviewed for a number of countries, with particular emphasis on how they treat the environmental issues.

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Cambridge University Press, 1987.

14 See R.L Kenny, The Art of Assessing Multiattribute Utility Functions, 'Organizational Behavior and Human Performance', 9, 267-310, 1977; EPRI, Operational Procedures to Evaluate Decisions with Multiple Objectives, Report EA-5433, EPRI, Palo Alto, Ca, 1987; H.M Merril, The Trade-Off/Risk Method in Power System Planning, Power Technologies Inc., Schenectady, NY., 1989; and 1985 Generic Comparison of Technologies, Generation Planning Pacific Gas and Electric, San Francisco, Ca, 1985.

Power Sector Investments In Selected Countries

France

In France electricity supply is highly centralized, with the électricité de France being responsible for around 90% of electricity output and 95% of distribution. Hence investments by that authority are critical to the sector, and its investment planning and pricing models are renowned throughout the world. The generation planning methodology of the EDF is summarised in Figure 1. A distinction is made between the 'global strategy', which looks at overall investments and the 'individual projects' models, which evaluate both specific projects in detail, as well as regulating schemes such as individual pumping projects and real-time optional tariff proposals. This is represented on the vertical axis. On the horizontal axis, there is a distinction between dynamic long term modelling and detailed operations modelling. Thus there are four quadrants. Global strategy regarding long term issues is addressed in the MNI (Modèle National d'Investissment) and questions of detailed operation are analyzed in the MNR (Modèle National de Régulation). On the individual projects side, there is the Blue Note, which is a standard investment appraisal approach for marginal investments in power, and a 'specific models' module, that evaluates specific regulating schemes, such as those mentioned above.

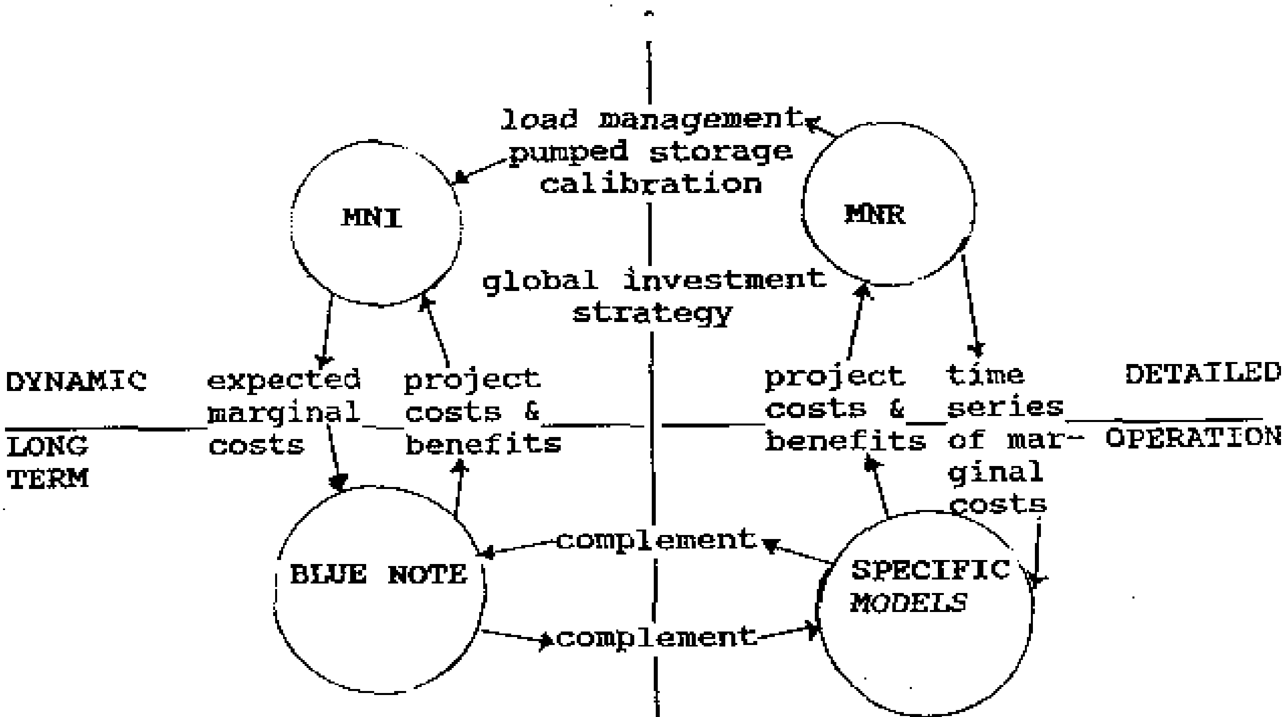


Figure 2: Generation Planning in the EDF

Source: B. Montfort and P. Lederer (1985)

The MNI model is closest to the energy supply models discussed in Section II. It has evolved over time and presently has an optimal control structure[15]. The model minimises the discounted expected costs of generation to meet a given demand over a period of 40 years. Environmental costs appear only in so far as they affect the costs of generation for a particular plant through increased mitigation expenditures. Among the other models, it is the Blue Note that would be most relevant to the analysis of environmental factors, although dispatch and regulation decisions could be affected by such considerations as well. This project appraisal module, however, does not evaluate the environmental damage costs at all, or examine the alternative environmental mitigation costs or accident risks in any detail. As far as can be ascertained, it takes the costs as given and then evaluates the project, optimising the design to maximise the net benefits to be obtained.

Hence the formal planning procedure for power in France does not address the environmental issues other than through the inclusion of specified mitigation costs as part of project costs. Discussions with EDF officials and those involved with the French environmental policy indicate that the latter influences energy policy in two ways. First, the broad parameters within which energy planning is carried out are influenced by other considerations, such as self-sufficiency and the environment. Thus the decision to emphasise nuclear power in its investment programme (which now accounts for around 74% of total generation and is planned to go up to nearly 80% by 2000), is partly a political decision. This reflects itself in the planning routines in a number of ways. First the candidate plants over which the optimisation is carried out exclude certain options and include others that are considered more desirable. Secondly the discount rate used can influence choices to a large extent. For example, nuclear plants' costs are sensitive to the discounted costs of decommissioning. In a recent survey of the costs of alternative power plants carried out by the IAEA, it was reported that France used a real discount rate of 8%. Most other countries surveyed had a rate of around 5%, with the UK discounting decommissioning costs at 2%.[16] Incidentally, it is interesting to note that the construction cost for a nuclear plant in France was the lowest of any of the 12 countries surveyed, being about 70% of the average cost for all the

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15 See B. Montfort and P. Lederer, Generation Planning at Electricité de France: A Sharper Focus for the Coming Decades, in 'Planning the Electricity Sector', (V. Fremaux and P. Lederer (eds.), Electricité de France, Paris, 1985.

16 See G. Woite, Projected Costs of Generating Electricity from Power Stations for Commissioning in the Period 1995-2000, IAEA, Vienna, 1989.

countries. Cost variations can arise for many reasons in this context, and variation in environmental mitigation costs is often one of them[17].

The other way in which environmental factors are brought into power investment planning is through the use of Environmental Impact Analysis. This is mandatory for all investments of over 10 million French Francs. The guidelines for the EIA are comprehensive and require several variants of the project to be considered from an environmental point of view. There is, however, no valuation in monetary terms of the environmental impacts at this stage.

Germany

Although the monetization of environmental damage estimates has been taken further in the Federal Republic than in any other European country, it has not been much applied to power systems planning as such.[18] Federal legislation now requires a full cost benefit analysis of all large projects, including a monetary estimate of the social costs such as air and water pollution. However, as power planning is a regional or 'land' issue, the law has not applied to power investments. Instead, various planning and evaluation methodologies have been used in the different states. Whatever method is used, it has to take account of the very strict federal emissions regulations that are imposed on power plants under the 'Bundesemissionschutzgesetz'. In addition to the conventional cost minimisation models for selecting power sector investments, there is a substantial use of cost effectiveness and risk analysis techniques. In the state of Baden-Wüttemberg, for example, a strong dialogue has developed between the power and energy planners and the authorities that determine the environmental regulations. Cost effectiveness and risk analysis models have been employed to identify the least cost solutions of meeting certain energy supply requirements,

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17 For details on valuing the costs and benefits of nuclear power plants see, N. Evans and C. Hope, Nuclear Power: Futures, Costs and Benefits, Cambridge University Press, Cambridge, 1984.

18 Estimates of the social costs of energy consumption have, however, been made. See O. Homeyer, Social Cost of Energy Consumption: External Effects of Energy Consumption in the Federal Republic of Germany, Springer Verlag, 1989; and U. Kallenbach and E. Thōne, Gesundheitrisken der Stromerzeugung, Verlag TUV Rheinland, 1989. An example of a social cost benefit study in the energy field is that of the substitution of individual heating by district heating in Berlin carried out by Professor Wijne of the Technical University of Berlin (personal communication).

subject to various permitted levels of emissions and of accident risk.[19] The advantage of this dialogue is that the regulations themselves are drawn up with a greater awareness of the costs that they impose on society in terms of higher energy investment and operating expenditures.

Once projects have been selected in principle, they are subject to environmental impact analysis in all states. At present there are no directions for the preparation of the EIAs, but a group of experts is currently drawing up a set of guidelines.

Sweden

Sweden has proceeded in its electricity planning, to a greater extent than most developed countries, by defining the options through legislation and central directives. In 1980 a public referendum called for the phasing out of all 12 of the country's nuclear power plants by 2010, a decision that was ratified by an Act of Parliament. This act also set several other objectives:

(a) no further development of hydropower on Sweden's four remaining major rivers. Currently hydropower accounts for 50% of Swedish electricity production;

(b) a reduced consumption of oil in power generation;

(c) strict environmental standards that call for no net increase in carbon dioxide emissions in response to the threat of global warming;

(d) increased use of renewable energy sources such as solar, wind and gasified biomass.

Once these parameters are set, the planning of the power sector necessarily requires an integration of increases in generation and improvements in efficiency. The Swedish paper discussed earlier in this report[20] does just that. It investigates a number of options or scenarios, some of which would permit the achievement of these objectives and estimates the costs associated with them. However, it does not identify the instruments that would be required (such as prices, taxes and subsidies) to ensure that individuals and firms do indeed undertake the efficiency measures that are required, or the costs of those measures. The latter could be so high that the measures are, in fact, infeasible.

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[19] See, for example, A. Voss et al., Perspecktiven der Energieversorgung, Gutachten, Stuttgart, 1987.

[20] Bodlund et al. (1989).

The United Kingdom

Until the break-up of the Central Electricity Generating Board (CEGB), that body was responsible for power systems planning in the UK. Although it did not model environmental costs explicitly, the linear programming models used to determine the least cost expansion plans did include the costs of environmental protection, in accordance with any required standards. It also carried out something akin to an environmental impact analysis for internal use. The optimisation of discounted present value of generation costs was carried out for many years using a real discount rate of 5% as required by the UK treasury (this rate has now risen to 8%). The CEGB also developed a fairly sophisticated coal dispatch model for use in the power stations.

In preparation for the privatisation of the electricity sector, two generating companies have been set up in the UK out of the old CEGB. In addition, there will be private distribution companies, based on the 'electricity boards', and a private central grid company responsible for the efficient purchase of power from the generating companies and its sale to the distribution boards. With these changes, the responsibilities for power planning have also altered. The generating companies now plan power supply to maximise discounted profits, and use a discount rate that is much higher than 5%. A figure of 15% has been mentioned as being typical. In addition they take a different view of the uncertainty of future costs from the public sector. Both these factors are reflected in the inability of the government to sell off its nuclear power installations to the private sector. The high discount rate militates against nuclear plants compared to coal fired plants. Uncertainty about future decommissioning costs also appears to play a very important part in private sector decisions. Hence, in spite of the high discount rate used by that sector, and the fact that these costs are far in the future, the 'risk premium' attached to them is so much greater that they have a more negative impact on private sector decisions.

As far as the fossil fuel plants are concerned, the government has acted on the European Commission's Large Combustion Plant Directive, which requires, (a) specific limits on emissions from new plants and (b) reductions of emissions from existing plants in accordance with a timetable - e.g. $SO_2$ emissions to be reduced by 20% by 1993 and 40% by 1998. Given these overall reductions, the government allocates 'cuts' to each company, which is then free to achieve its reductions at lowest cost. Since this is a relatively new procedure for the companies, they are now in the process of developing models similar to those used in the US to achieve this optimisation. However, the overall effectiveness of such a decentralisation procedure will depend on how 'efficient' the allocation in cuts by the central government is.

As far as risk analysis is concerned, this has been mainly used to model the risk of failure of supply. Although detailed calculations of accidents attributable to each mode of generation exist, and have been used in piecemeal comparisons between plants, there appears to be no formal modelling of environmental risk at the systems level.

The United States

In the United States, power systems planning is carried out at several levels. There are the investment decisions taken by individual power companies, power dispatch and exchange agreements between companies within a power pool, and systems modelling by the Department of Energy and the Environmental Protection Agency, to determine the regulatory framework within which energy policy and environmental regulations are determined.

At the individual company level, there are a range of modelling techniques in use. These are exemplified in the Pacific Gas and Electric Company's Generic Comparison of Technologies referred to earlier. This company reviews its use of benefit cost analysis, risk assessment methods, and multi-criteria analysis, among other techniques. These are all used from the private point of view, and so attention to environmental factors only arises if they are requirements imposed by the regulatory authorities, or if there is some perceived gain in terms of 'green consumerism'. It is also acknowledged that all the sophisticated methods used are only aids to the decision-makers, who may ignore their findings if more important considerations arise.

For the power pools there are a number of models available, such as ARGUS, BNL, EGEAS, and WAGP. For dispatch modelling there are models such as ICARUS. These have been developed by: Argonne National Laboratory (ARGUS and ICARUS); by Brookhaven National Laboratory (BNL); the Electric Power Research Institute (EGEAS) and by Westinghouse (WAGP). Their use is not limited to the electric utilities, who look for least cost methods of meeting given demand, subject to the set of regulations imposed, but also by the regulatory authorities, who use them to ascertain the costs of alternative regulations, such as trading bubbles, ambient air quality constraints and the use of sulphur taxes.

Thus there is a widespread use of modelling and decision-making techniques in the United States at many levels, and this is extensively supported by research into the models and techniques themselves. The extent to which they can be used in developing countries, however, is uneven. Some, such as the BNL and ICARUS models have already been used and others such as ARGUS could well be used. However, the more sophisticated risk analysis models and the multi-criteria techniques would require, in many countries, a better appreciation of how such techniques can be of assistance in the decision-making process.

## IV CONCLUSIONS AND RECOMMENDATIONS FOR POWER SYSTEMS PLANNING IN DEVELOPING COUNTRIES

In this paper the models and current practices in the field of power systems planning have been reviewed, with particular reference to the treatment of environmental issues and with a view to the applications of these techniques in developing countries. In designing a power generation programme one should, ideally, estimate all the costs of a power generation programme, including the environmental costs, and then calculate, for each programme, the expected net costs of meeting a given supply. This analysis has, however, to be supported by other studies, particularly those that evaluate the risk and uncertainty associated with the programme. The individual studies then feed into the decision-making process, where other considerations of a political or strategic nature will be brought in. At this stage the analyst has little to contribute, except perhaps to indicate the trade-offs being made between the alternatives. This can be done in an ad hoc way, to say that if option 'X' is being chosen on, say, self-sufficiency grounds in preference to 'Y', then the additional cost of that option is 'Z' and the environmental costs are 'A,B,C...'. The representation of trade-offs can also be carried out in a more formal way by using multicriteria analysis, but that is less common.

Looking at the cost evaluation of the power programmes first, one finds different environmental costs arising as a result of the use of different energy sources for electricity. These have been described in Table 1 in the report. There are techniques available to estimate the costs associated with each of these impacts in monetary terms, but the application of these techniques is hardly ever practised in power systems planning. Instead, four alternative approaches are taken.

The first is to identify the 'mitigation' costs, such as those of air pollution control, or water quality protection in the case of hydro dams, and include them in the cost evaluation. The difficulties with this are: (a) mitigation costs can be assessed more easily for some technologies than others, and so choices are biased in favour of those for which the costs cannot be easily be assessed, and (b) even if the costs were available for all technologies, it is by no means clear that the residual impacts (i.e. the impacts of the pollution that has not been mitigated) would, in each case, be of equal importance. Hence taking just this route can lead to biases of choice but, if done with an awareness of these problems and with an attempt to reduce these biases, it can provide useful information to the planner.

The second is to look for the cost minimising alternative, subject to certain environmental constraints. By varying the constraints, one can then measure the costs of attaining different levels of environmental protection. There are a number of models that proceed along these lines. Most of them have a linear programming structure and most of the 'constraints' apply to thermal power - limits on emissions or on air quality levels in given regions. Hence they are not particularly useful for hydropower planning. It is worth noting that many of the models of this kind look at the energy sector as a whole, and power is just one of the sub-sectors. Inspite of its limitations, this approach can also assist the power planners, particularly by identifying the costs of environmental protection.

In the third and fourth approaches the environmental costs are not looked at directly, but the environmental impacts of each investment plan are estimated systematically. This provides useful material to the planner, but it is not enough. Since more relevant information can be obtained with fairly accessible models, it would be better to use the latter, perhaps in conjunction with an 'impacts' module.

In addition, a distinction is made between models that look only at the supply side, and those that look at both demand and supply. These integrated models often use the supply models such as WASP but link them to a demand and energy balance modules. Given the high returns to demand management and energy conservation in power systems planning, and especially from an environmental point of view, the use of such models is particularly valuable in this context.

Cost minimisation models are, however, only one of the tools that a power systems planner needs. In most advanced countries, some systematic investigation of the risks of different options is undertaken. The models used for this vary a lot but most attempt to examine the trade-off between reduced risk and increased cost of power options. The overall impression one gets is that these models are useful and interesting, but that their results cannot be easily conveyed to those responsible for taking the decisions. These decision-makers look at a number of other factors and the task of presenting complex information from a number of analytical tools in a clear and concise fashion remains an art.

A brief review of the policies with regard to power planning in selected developed countries reveals that, inspite of the use of sophisticated models, decision-making is heavily influenced by strategic considerations, which can, in some cases, include environmental factors. Nevertheless it would be incorrect to assume that the systems planning and risk analysis models are redundant. They can be of great value, especially when there is a dialogue between the power planners and the environmental regulators.

Implications for Developing Countries

What lessons can be learnt from the models and techniques reviewed here about the use of the techniques in developing countries? There are three key points that should be noted. The first is that a number of the systems models described in this report are already being installed and used in developing countries. This is apparent from Tables 2 and 3, where the list of applications (actual and potential) is reported. Hence there is already a considerable amount of interest in the use of energy planning models with environmental features. The second is that there is no single model that is applicable and that will provide 'the' answer to the questions being posed here. At the very least, one should look at optimisation cost models with environmental constraints and risk analysis models. Within the former there are some that serve a general function and others that can be used for the detailed analysis of particular issues, such as the optimisation of coal fired plants. The particular model to be used will depend on the question to be answered. Finally, it is as important to train planners and decision makers in the interpretation of the results of the models, as it is to transfer the capability to operate the models. Certainly one of the most useful things that can emerge from such an exercise is a better communication between those responsible for power and energy in a country, and those responsible for the environment.

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