AN APPLICATION OF MATHEMATICAL PROGRAMMING TO THE CHOICE OF INVESTMENT:

The Case of the Electric Power Industry in Korea

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I. INTRODUCTION

I. Background of the Study

The choice of investments has always been a major concern of economists and businessmen. Substantial development of analytical techniques for the choice of investments in public utilities has been achieved in recent years. The most important contributions have come from two newly developed techniques: *cost-benefit analysis* and *mathematical programming*. Cost-benefit analysis is a practical way of assessing the desirability of projects, where it is important to take a long view and a wide view. Although cost-benefit analysis has been useful in determining the desirability of multiple purpose

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projects, the scope of the analysis has mainly been restricted to the level of individual project evaluation.[2]

The development of mathematical programming has provided an efficient technique of choosing a "good" alternative from among a large number of possible ones. Such efficiency of choice is essential in dealing with the choice of investments in an industry involving different combinations of techniques, and of sizes and locations of plants. Although the computational procedures for *non-linear* programming have continually improved, *linear* programming has mainly been used for the problems of industrial management because of the simplicity of computation. Applications of linear programming to business and industrial management began in the early 1950's and have had a remarkable growth in the last decade.[2] Although most applications have remained in the problems of single plants or firms, attempts are being made increasingly to apply linear programming to problems of single industries or interindustry level.

The application of linear programming to the choice of investments in the electric power indutry has mainly been carried out by French economists and operations researchers.[3] They have divided the problems of the choice of investments into "marginal" and "global" problems and applied linear programming to the "global" problem.[4] Of course, it has

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(1) For the contribution and limitations of cost-benefit analysis, see A.R. Prest and R. Turvey, "Cost-Benefit Analysis: A Survey," *Economic Journal, Dec.* 1965.

(2) G.B. Dantzig, *Linear Programming and Extensions* (Princeton, J.J.: Princeton University Press, 1963), pp. 28—29.

(3) P.Masse and R. Gibrat, An application of linear progromming to Investments in the Electric Power Industry *management Science* Jan. 1957.

J.R. Nelson (ed.), *Marginal Cost Pricing in Practice* (Englewood Cliffs, N.J.: Prentice Hall, 1964), Chapter 1 (M. Boiteux), Chapter 9 (P. Masse), Chapter 10 (M. Boiteux), Chapter 12 (P. Masse and F. Besciere).

P. Masse, *Optimal Investment Decisions: Rules for Action and Criteria for Choice* (Englewood Cliffs, N.J.: Prentice Hall, 1962), Chapters 4 and 8.

(4) Regarding this methodology, see: R.L. Meek, "The Allocation of Expenditure in the Electric Supply Industry: Some Methodological Problems," *Scottish Journal of Political Economy*, Feb. 1963.

been well recognized that application of linear programming to such a complex problem has only limited value. All we can hope for, at least at this moment, is a fairly generalized picture of the main lines of development which a long-run development plan ought to follow.

II. Scope of the Study and Problems to be Analyzed

For this study, the electric power industry is taken as the unit of analysis. Feedback effects via other industries are disregarded. Hence the scope of this study is narrower than an industry study and broader than the evaluation of individual projects. Of course, it is not difficult to see that the choice of investments peculiar to the electric power industry is not independent of certain wider problems of choice which have to be solved by the economy as a whole such as the determination of the rate of capital accumulation and the allocation of the total amount of capital among different industries or different forms of energies. Also, an estimate of the future demand for electric power cannot be made adequately from a partial equilibrium study of the existing power market alone but must also take into account the probable changes in output of the electric-power-using industries. Therefore, one of the shortcomings of the single-industry approach is that the result may not be consistent with the development of the rest of the economy. Two methods are often used for treating the connection between an industry and the rest of the economy. One is in the form of quantities (for example, set a target for each industry) and the other is in the form of prices (for example, a minimum social return required on investment). It is thought that prices provide a more desirable means of coordination than quantities, since they allow more scope for the working of the market mechanism so as to result in a more nearly optimal allocation of resources among the various industries of the economy. Primary reliance on targets and quantitative adjustments tends to obscure the possible alternative uses of resources and increases the need for governmental intervention. In practice, however, the form of quantities is often preferred to the form of prices mainly because of the simplicity of using it. That is to say, it is very hard to evaluate the social returns on investment in many cases, while the targets for major industries may easily be derived from the input-output type approach with some technological knowledge. While the shortcomings of the single industry approach should be borne in mind, it is also important to recognize that, with the individual industry as the unit of analysis, it becomes possible to focus upon some interesting specific investment problems.

First of all, where more than one basic method of producing a certain good exists, the problem of choosing between various broad lines of development for the industry as a whole becomes an essential investment problem. In the electric power industry, this is the problem of how the proportion of the total output of electric power produced by coal or oil-fired thermal plants, hydropower plants, and nuclear power plants should be varied over time.

Second, where economies(or diseconomies) of scale exist, the determination of the size of plant also becomes an important investment problem. Furthermore, the determination of the size of plant requires the simultaneous consideration of the problem of the siting of plants, since transportation cost is a major factor offsetting economies of scale.

The third problem is the timing in introducing additional capacity to meet the anticipated growth of demand.

Obviously, all of these problems are interrelated. The choice of production technique interacts with the problems of when, where, and how large, and these require a simultaneous treatment. It is almost impossible to provide formal models which take into account all the problems at once. This study is only an attempt to investigate some of the essential features of these investment problems in the electric power industry in Korea. Furthermore, it should also be mentioned here that this study is mainly concerned with the economic consequences of investment decisions. Socio-political consequences certainly have a great influence on investment decisions, particularly in developing countries. Hence, in principle, economic consequences must be studied along with the cultural, political, and social effects. Socio-political considerations are, in some cases, decisive. In any case, we cannot ignore them completely, since we cannot assume that investment decisions have no extra-economic consequences, nor that economic consequences are all that matter. Hence, although economic consequences are the major concern of this study, some of the extra-economic consequences should be kept in mind.

III. Method of Approach

Mathematical programming is used as a tool of analysis in this study. Although the programming method has mainly been applied to problems of single plants or firms, the method itself is also useful for industry wide and interindustry analysis. In fact, mathemaical programming is being employed increasingly to the study of the allocation problems of single industries and interindustry level.(5)

For mathematical programming, simplification of the problem is essential and the viewpoint of the study is normative. One alternative method is simulation. Simulation is basically descriptive and can incorporate a large amount of detail which is hard to analyze by mathematical programming

(5) Notable examples of application of linear programming to the problems of single industries are:
J.M. Henderson, "A Short-Run Model for the Coal Industry," *The Review of Economics and Statistics*, Nov. 1955.
J.M. Henderson, *The Efficiency of the Coal Industry* (Cambridge, Harvard University Press, 1958).
P. Masse and P. Gibrat, "Application of Linear Programming to Investments in the Electric Power Industry," *Management Science*, Jan. 1957.
A.S. Manne and T. Victoritsz, "Chemical Processes, Plant Location and Economies of Scale," in A.S. Manne and H.M. Markowitz (eds.), *Studies in Process Analysis* (New York, 1963).
An outstanding example of application of linear programming to the problems of interindustry analysis is H. Chenery and K. Kretschmer, "Resource Allocation for Economic Development," *Econometrica*, Oct. 1956.

(random elements, non-convexities, etc.). For the following reasons, however, I have chosen the programming method:

(1) Mathematical programming is inherently more convenient for analyzing efficiency problems. It has the ability of cutting across the enormous combinatorial range of alternatives.

(2) Mathematical programming provides insight and identifies attractive new alternatives, while simulation must stay close to the initial trend projections.

(3) Sensitivity analysis and parametric programming reduce the purely normative nature of programming and provide some of the kinds of information needed by planners.

(4) The recent developments in mathematical programming, including such techniques as integer programming, chance-constrained programming, have greatly increased the variety of particular cases that can be incorporated into mathematical programming.

(5) Mathematical programming provides shadow prices as its dual solutions. Since the shadow price of a factor is a measure of its opportunity cost or its marginal product, the concept of shadow prices has great value for improving resource allocation in developing countries where market prices do not provide correct guides for investment decisions.

The object of this study is to apply mathematical programming to the problems of industry wide investment decisions in the electric power industry in Korea. In any sense, however, it is not our intent to find the "best" choice for the industry. The imperfections and limitations of the approach do not allow us any attempt to find the "best" choice. They include:

(1) The lack of a universally accepted set of value judgments from which we can start the analysis.

(2) The complex interrelations between variables and the extreme simplifications required in the programming.

(3) Uncertainties.

(4) The exclusion of extra-economic consequences.

Despite these numerous limitations, an attempt to apply mathematical programming to practical problems is in itself interesting and may also be quite instructive. The advantages of such an attempt are well expressed by Arrow as follows:

> The very solution of particular decision model will change the state of knowledge available, and so enable us to look at the original problem, or related problems, in a new light. Indeed, I suspect in a great many applications, the principal virtue of operations research has been to force a rethinking of the situation, and the gain may well have been due as much more to the new knowledge unearthed by the forced new analysis as to the formal apparatus of the optimization process.[6]

II. SOME BASIC CONCEPTS FOR THE ANALYSIS

I. Objective Function

In mathematical programming, we require an objective function which will enable us to select one solution as better than another. Hence, the choice of objective functions has a prime importance for this approach. The problem in choosing an objective function is essentially to determine the relationship of the problem to a higher-level problem. Therefore, the validity of an objective function must be evaluated in terms of the objectives of a larger system. For a single-industry approach, it means that the choice of an objective function must be done under the consideration on objectives of development of the country. Yet this is not often done nor is it easy to do. One reason it is not done is that efforts are not made to learn what

(6) K.J. Arrow, "Decision Theory and Operations Research," *Operations Research*, December 1957, p. 766.

the objectives of development of the country really are. Then it is not easily done because the objectives may be diverse and, in many cases, inconsistent. It is certainly necessary that such objectives should be set as clearly as possible and the relationships of an industry to these objectives should be investigated before factoring out any subproblems. "Our problem must be stated as if it were closed, so that it can be solved, and yet its elements must contain within themselves the possibility of fitting into a larger model."[1]

1. Maximization versus minimization

In practice, two forms of objective function are used in programming. One is the maximization of benefits given resource limitations and the other is the minimization of costs for attaining a given target.

The maximization criterion is usually advocated for bringing about the optimum allocation of available resources among the various sectors of the economy. Moreover, its application ensures the most efficient operation of the sector in which the resources are invested. In spite of these advantages, I have chosen to use the minimization criterion, more specifically, the minimization of present values of future cost flows as a unique objective under given factor prices with demand and capacity to be expanded over a finite time horizon. The following reasons force me to do so:

(1) By separating the problems of pricing from those of the choice of investments, it would be possible to focus upon the analysis of latter problems.

(2) It is assumed that the demand for electric power in Korea is quite inelastic with respect to the price of electric power within a reasonable range and largely depends on the overall development plan and planned changes in the economic structure. Hence, it is not unreasonable to see the

(1) K.J. Arrow, "Decision Theory and Operations Research," *Operations Research*, Dec. 1957, p.773.

problem as the choice of investments which minimizes costs for attaining the targets.

2. Present value versus annual cost

Sometimes the minimization of total annual costs is used as a criterion instead of the minimization of present values of future cost flows. This criterion simply says that we should try to minimize the sum of annual running costs and 1/T of the initial costs where T represents a predetermined period. The major drawbacks for this criterion are that T is fixed more or less arbitrarily and has no scientific basis and that, in fact, costs are bound to vary significantly from year to year during the life of the equipment. Hence, the present-value criterion is at least conceptually superior although it is questionable to claim superiority in practice because of the difficulties of choosing an appropriate discount rate and of predicting divergences of future operating costs with sufficient accuracy to make such a refinement really worthwhile.

3. Cost estimation and shape of the cost function

The adaptation of the minimization of the present value of future cost flows as an objective creates a number of questions to be answered. The major questions are: how to define costs and how to estimate costs in practice. Regarding the first question, I shall simply follow the conventional practice. Houthakker divides the costs of the electric power industry into four categories: energy costs, capacity costs, consumers' costs and residual costs.(2) For this analysis, however, the consumers' costs and the residual costs will be ignored. The cost of short supply will not get into the formal model directly but it will be reflected in the selection of the level of guarantee in the model with uncertainty.

For the estimation of costs, we face two major problems. One is how to get relevant information as to the actual costs and the other is to determine

(2) H.S. Houthakker, "Electricity Tariffs in Theory and Practice," *Economic Journal*, March 1951, pp. 2—3.

the shape of the cost function which can be used in the model. Three sources will be searched for data. Of course, the primary source is the data accumulated for the electric power industry in Korea. Then the lack of data will be supplemented by the experience in other countries such as Taiwan. Technological information will be another source. As to the shape of the cost function, linear approximaton will be mainly used. The reason is partly because of the relative efficiency of computation by the simplex method and partly because the acceptance of the sophisticated cost function will add to the complexity of the model but may not be more meaningful than the simple one unless the accuracy of detailed date is improved. One of the major disadvantages of using the linear cost function is that it overlooks economies(or diseconomies) of scale and indivisibilities. Hence, the piecewise linear function will be introduced and some decision variables will be required to be integer valued. In spite of the recent development in algorithms for integer programming, the efficiency of the algorithms is still somewhat unsatisfactory. So it is desirable to restrict integer requirements as much as possible.

4. Benefits other than electric power

It seems obvious that the minimum-cost criterion is meaningful only when we can assume that all alternatives bring exactly the same results. However, in practice, none of the alternatives are exactly comparable owing to differences in their technical and operational characteristics. These differences are very serious in the choice between thermal and hydropower plants. Because of the lack of adequate irrigation and flood control systems in Korea, the benefits other than power generation from the construction of hydro plants are, in general, so great that we cannot simply disregard them. The benefits would not be directly reflected in the objective function of the models because of the variability of each hydro site. In this study, we shall try to determine a rough estimate as to the average benefits other than power generation should be if the development of hydropower (which is unjustified for the purpose of power generation only) can be justified.

5. Extra-economic objectives

As already mentioned, extra-economic objectives certainly play an important role in practice. For instance, in many cases, political considerations to meet the demands created by various regional and social groups are more influential than the costs in the choice of investments. The extra-economic objectives, however, will not be reflected in the objective function in this analysis. It is my intention to consider extra-economic objectives as constraints which require a departure from economic efficiency. I suspect this is one way of measuring the significance of those objectives.

II. Discounting

Since we are concerned with future cost flows, there must be a device to handle costs incurred at different times. The general practice is to discount future cost flows. Thus, the choice of a discount rate has a great influence on the choice of investments. Although there exist many time discounting techniques, it is not easy to choose an appropriate rate to be used.

It is often suggested that a rate determined in the capital market be used. However, there are a number of different market rates, each of which reflects special situations and factors. Furthermore, from a national welfare point of view, the market-determined rate may not conform to the social rate because (a) there are costs and benefits of private investment which the private sector is not forced to pay or cannot reap and (b) there is the possibility that government takes group-desired action which by its nature cannot be undertaken by society acting individually. The concept of the social opportunity cost of capital is intended to incorporate these broad issues. However, the task of estimating this cost is difficult not only because of the imperfections of the market, but also because social values are involved. Prest and Turvey state in their survey:

> Discussion about the social rate of time preference, social opportunity cost, etc., do not cut very much ice in most empirical work, and we have not been able to discover any cases where there was any convincingly complete application of such notions.[3]

Also, there is much controversy as to whether the discount rate used should include a risk premium or not, and if it should, how to identify the risk component in practice.[4] It is not my intention to delve deeply into the problems of the selection of an appropriate discount rate. Perhaps the most reasonable way out for this kind of study is to examine the sensitivity of different discount rates within a certain range.

III. Time Horizon and Salvage Value

In evaluating alternative investment plans, the discounted cost flows must be summed up over a finite or infinite time period and, therefore, the length of planning horizon has an influence on the choice of investments. In this analysis, the planning horizon extends 15 years. Thus the costs may be summed up for the planning horizon in general much less than the life of the planned installations.[5]

If this the case, the solutions tend to favor less capital-intensive and shorter life techniques. In order to avoid these effects, the discounted value of the remaining life of plant is taken as its salvage value and subtracted from initial capital costs. In calculating the value of the remaining life of

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(3) Prest and Turvey, *op. cit.*, pp. 699-700.

(4) A detailed analysis of the risk problem is in: J. Hirschleifer, J.C. DeHaven, and J.W. Millman, *Water Supply* (Chicago: University of Chicago Press, 1960), pp. 139—141.

(5) In other words the Salvage value is ignored.

plant, the principle of the straight line depreciation is applied.[6] In effect, the system is only forced to pay for that portion of capital services that is utilized within the fixed planning horizon of the model. In principle, the salvage value of any plant has nothing to do with the initial capital cost because the initial cost has to be taken as sunk cost. The salvage value has to be computed on the basis of the marginal value of energy at the end of the planning horizon. In practice, however, there is little chance of knowing the marginal value of energy in a distant future. It is general practice to compute the salvage value on the basis of initial capital cost. This practice is, of course, very far from the actual facts but by the very nature of the present value calculation, an incorrect method relating to a distant future has very little effect on the result of calculation.

IV. Uncertainty and Sensitivity Analysis

The choice of investments involves a high degree of uncertainty such as future demand, technical progress, factor prices, water flows, etc. The longer the period over which the planning process extends the more fundamental is this aspect of uncertainty. Hence, the choice of investments in the electric power industry requires an explicit treatment of uncertainty.

For the purpose of the analysis, uncertainties are divided into two categories. A first category of uncertainties consists of those for which we can derive relatively precise laws of probabilities from past information. The flow of a river belongs to the first category. When we have the probability distributions of the uncertain variables and it is not absolutely essential only highly desirable that the constraints be satisfied, then chance-constrained programming technique can be used to transform the uncertainties

(6) For the case in which the obsolescence rate is high, the sum-of-years' digits method or the double declining balance method can be used for absorption of a high percentage of initial capital cost in the early years than in the succeeding years.

to certainty equivalents. The crucial difficulty in using the chance-constrained programming technique is in choosing the probability level to be attained. In principle, the probability level should be the point where the marginal penalty cost for not meeting the demand equals the marginal cost of increasing the level. However, in practice, the computation of the marginal cost for not meeting the demand for electric power is very difficult.

A second category of uncertainties eludes the laws of probability. A typical second category of uncertainties is the future course of nuclear energy, with respect to performance as well as costs which cannot be outlined by any extrapolation from the past. The future demand for electric power may be included in the first category in advanced countries. However, in developing countries which are experiencing drastic structural changes, it may be more reasonable to include it in the second category. Sensitivity analysis is the only technique available for taking into account these uncertainties.

Sensitivity analysis handles the uncertainty in a different manner. Instead of relying on such additional information about the variables beforehand, this technique starts with the single "best estimate" of each variable and calculates the effect on the final result of changing the value of one of them. Then an estimate is made of the likelihood that those values of the altered variable which cause significant changes in the results will occur. Sensitivity analysis is particularly useful when the variability of the elements is difficult to estimate. Given the uncertainty in choosing each parameter in the model, it is prudent to be concerned with the effects of taking decisions on the basis of incorrect parameter estimates. Sensitivity to variations of parameters gives a useful basis to the decision-makers. Hischleifer says:

> As a practical alternative…and it is vital to make at least this much allowance for uncertainty the calculations should be repeated under a number of different assumptions about the unknown values of the most crucial elements of the problem. This is called "sensitivity testing," and

wise procedure would be to check sensitivity of the calculations to construction-cost changes, weather variation, discount rate, etc. It is often useful to note differences in outcome between optimistic assumptions all along the line, neutral assumptions and pessimistic assumptions.(7)

In this study, the uncertainty problem will be mainly handled by the sensitivity analysis technique and the idea of chance-constrained programming will be incorporated whenever it is possible.

V. Peak Demand Problem

The demand for electric power fluctuates widely over time. In addition it is economically impossible to store electric power in significant quantities. Therefore, it is the peak demand which determines the required capacity of the electric power industry. On the other hand, a part of the available capacity will not be utilized during the off-peak period. Hence, the operational level of each type of plant during the off-peak period must also be determined. Here we have a typical investment problem where we must look for a joint investment and operating optimum. In the programming models, therefore, the level of operation during the off-peak period as well as the capacity of each type of plant become decision variables.

III. MODELS

I. A Linear Programming Models with Certainty and Zero Gestation Period

1. Decision variables

As explained in the previous chapter, the levels of operation as well as the levels of capacity become decision variables in the electric power industry.

(7) Hirschleifer, DeHaven, and Millman, *op. cit.*, pp. 165—166.

The level of capacity in year depends on two kinds of decisions: the capacity to be built and the capacity to be retired between years 1 and i. A part of the capacity available must be idle during the off-peak period. Thus, descisions have to be made as to the operational levels of different types of plants during that period. Here we have three kinds of decision variables as follows:

X_{ij}=capacity of type j plant to be built in year i;

Z_{ij}=capacity of type j plant to be retired in year i;

Y_{ij}=capacity of type j plant to be utilized during the off-peak period in year i.

2. Peak demand constraints

Since it is economically impossible to store electric power in significant quantities, the peak demand can be met only by investment on increasing installed capacity. That is, total available capacity must be greater than or equal to peak demand for each year. The available capacity in year i can be considered as a fraction of installed capacity in that year because a certain percentage of the system capacity should be out of service for regular maintenance and unexpected failures. For hydropower, the availability of installed capacity is also limited by the inflows of water into hydropower plants unless they have sufficiently big reservoirs. Thus, the peak demand constraints can be expressed as follows:

$$\sum_{j=1}^{n}\beta_j[A_j+\sum_{t=1}^{i}(X_{tj}-Z_{tj})]\geq E_i \qquad \text{for all } i \qquad (1)$$

where A_j=existing installed capacity of type j plant before the planning horizon

β_j=average technically feasible plant capacity factor

$\left[\text{i.e., } \frac{\text{average technically feasible capacity}}{\text{installed capacity}}\right]$ of type j plant

E_i=peak demand in year i.

Since $\sum_{t=1}^{i}(X_{tj}-Z_{tj})$ represents the net increment of capacity of type j plant between years 1 and i, the left-hand side of the constraint represents total amount of capacity available in year i. Thus, constraint (1) states that total available capacity in year i must be greater than or equal to peak demand E_i in year i.

3. Off-peak demand constraints

For each year, the level of operation during off-peak periods should be greater than or equal to off-peak demand. In other words, the following condition must be satisfied:

$$\sum_{j=1}^{n} Y_{ij} \geqq D_i \qquad \text{for all } i \qquad (2)$$

where D_i represents the off-peak demand for year i.

4. Capacity constraints for each plant

The level of operation of type j plant during the off-peak period in year $i(Y_{ij})$ must be less than or equal to the available capacity of type j plant in year i. Hence, we have the following constraint for each type of plant and each year:

$$Y_{ij} \leqq \alpha_j \left[A_j + \sum_{j=1}^{i} (X_{tj} - Z_{tj}) \right] \qquad \text{for all } j \text{ and } i \qquad (3)$$

where α_j represents the average technically feasible plant capacity factor of type j plant during the off-peak period. α_j may be different from β_j since regular maintenance can be scheduled to be done during the off-peak period.

5. Hydro potential constraints

Since we have only limited hydro potentials, the development of hydropower during the planning horizon cannot exceed the hydro potentials, i.e.,

$$\sum_{i=1}^{m} X_{ih} \leqq M_h \qquad \text{for all } h \qquad (4)$$

where h represents a group of homogeneous hydropower plants. it may be necessary to divide hydropower potentials into several groups of homogeneous plants in order to take care of diseconomies of scale in hydropower

6. Budget constraints

The availability of capital is the most crucial factor in determining the rate of growth and the choice of investments in the electric power industry. Hence, the scarcity of capital available for power development should be reflected in the model. This can be done by introducing budget constraint for each planning period as follows:

$$\sum_{i\epsilon q} \sum_{j=1}^{n} k_{ij} X_{ij} \leqq K_q \qquad \text{for all } q \qquad (5)$$

where k_{ij} represents the amount of capital required to construct a unit of capacity of type j plant in year i and K_q represents the amount of capital available for planning period q.

It may be worth looking at the economic implications of having budget constraints here. To have budget constraints in a programming model implicitly assumes that the funds available for power development are independent of the rate of interest. In many cases, however, budgets are not fixed but are roughly a function of productivity of the projects available and the rate of interest. Hence, economic theory tells us fixing the investment budget, independently of efficiency calculations as to the desirability of projects, is a procedure that can lead to serious economic error.

In reality, however, there are both economic and political reasons which can justify having a fixed capital budget. The economic justification is based on the existence of imperfections of capital market. In developing countries such as Korea, imperfections of capital market are so great that it is not rare that only a fixed amount of capital can be used for a specific purpose regardless of efficiency calculations. The second reason is a political one. As a practical matter, the problem of allocation of a national budget between major industries has not been based on efficiency calculations, but has been greatly influenced by political factors. Hence, the remaining decision in an industry is to select one or another alternative under conditions of either specific or maximum investment funds.

This addition of budget constraints to the programming model provides useful information for the evaluation of the budget allocation between industries and between periods in an industry. That is, the budget constraints give us the marginal value of capital in an industry for a specific period as their dual solutions(see next chapter). If such information could be obtained for major industries, the government can try to modify the allocation of funds so that the marginal values of capital in all industries approach equality.

7. Objective function

It is assumed that the objective of decision-maker is to minimize the present value of future cost flows. Roughly, the costs in the electric power industry can be divided into two groups: capacity costs and fuel costs.

The capacity costs include maintenance costs[1] as well as initial construction costs. If we construct X units of type j plant in year i, the initial construction costs will be $k_{ij}X_{ij}$. But if the planning horizon is much less than the life of the plant, the discounted value of the remaining life of the plant must be subtracted from initial capital costs as salvage value. Denoting this salvage value as s_{ij}, the cost of capital that is utilized within the fixed planning horizon of the model will be $(k_{ij}-s_{ij})X_{ij}$ for type j plant constructed in year i. Since the construction of a plant would require maintenance costs which are proportional to installed capacity, the discounted costs of maintenance within the planning horizon should also be included in the capacity costs. Denoting the discounted costs of type j plant constructed in year i as o_{ij}, the capacity costs of X units of type j plant constructed in year i will be $(kij-s_{ij}+o_{ij})X_{ij}$. Setting $c_{ij}=k_{ij}+s_{ij}+o_{ij}$, the total capacity costs during the planning horizon will be expressed as

$$\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}X_{ij} \qquad (6\text{-}1)$$

Contrary to the construction of new plants, some plants may be retired

(1) In the model, maintenance costs are assumed to be proportionate to installed capacity and independent of the level of operation.

during the planning horizon. If a plant is retired in year i, there must be corresponding saving of maintenanance costs for the rest of the planning horizon.[2] Let d_{ij} be the cost saving obtained by retiring a unit of type j plant in year i. Then the total cost saving due to the retirement of plants can be written

$$\sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}\, Z_{ij} \tag{6-2}$$

Next, we should consider the fuel costs which depend on the level of operation. Since Y_{ij} represents the level of operation of type j plant at off-peak time in year i, the total fuel costs of meeting off-peak demand can be written

$$\sum_{i=1}^{m}\sum_{j=1}^{n} f_{ij}(a Y_{ij}) \tag{6-3}$$

where f_{ij} represents the fuel costs per KWH generated by type j plant in year i and a represents the number of hours of the off-peak period in a year. On the other hand, all the available capacity will be utilized during the peak period. Hence, the fuel costs of meeting peak demand can be expressed

$$\sum_{i=1}^{m}\sum_{j=1}^{n} f_{ij}\left[b\beta_j \sum_{t=1}^{i}(X_{tj}-Z_{ti})\right]^{(3)} \tag{6-4}$$

where b represents the length of the peak period in a year in terms of hours.

Adding all the costs (or savings) explained above and discounting them back to year 1, we can obtain the objective function as follows:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\left[c_{ij}X_{ij}-d_{ij}Z_{ij}+af_{ij}\,Y_{ij}+b\beta_j f_{ij}\right.$$

$$\left.\sum_{t=1}^{i}(X_{tj}-Z_{tj})\right]\frac{1}{(1+r)^{i-1}} \tag{6-5}$$

(2) The salvage values of retired plants are ignored.

(3) It should be noticed that the fuel costs of meeting peak demand by the plants existed before the planning horizon are ignored in (6—4), since they are constant and independent of optimum solutions.

where r represents the discount rate.

By assuming that the fuel costs per KWH generated by type j plant is constant over the planning horizon (i.e., $f_{ij}=f_j$) we can rewrite (6-5) as follows:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}[\{c_{ij}+(m-i+1)b\beta_j f_j\} X_{ij}-\{d_{ij}+(m-i+1)b\beta_j f_j\} Z_{ij}$$

$$+af_j Y_{ij}] \frac{1}{(1+r)^{i-1}}\text{(4)} \qquad (6\text{-}6)$$

Let

$$\hat{c}_{ij}=\{c_{ij}+(m-i+1)b\beta_j f_j\} \frac{1}{(1+r)^{i-1}}$$

$$\hat{d}_{ij}=\{d_{ij}+(m-i+1)b\beta_j f_j\} \frac{1}{(1+r)^{i-1}}$$

$$\hat{e}_{ij}=(af_j) \frac{1}{(1+r)^{i-1}}$$

Then the objective function can be written

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\hat{c}_{ij} X_{ij}-\hat{d}_{ij} Z_{ij}+\hat{e}_{ij} Y_{ij}. \qquad (6\text{-}7)$$

The parameter $\hat{c}_{ij}$ represents the discounted capacity cost increased by the fuel cost required to meet peak demand during the planning horizon if type j plant is built in year i. On the other hand, $\hat{d}_{ij}$ is the discounted cost saving obtained by retiring one unit of type j plant in year i. The parameter $\hat{e}_{ij}$ simply represents the discounted fuel cost of operating one unit of type

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(4) Since $f_{ij}=f_j$,

$$\sum_{i=1}^{m}\sum_{j=1}^{n}b\beta_j f_{ij}\sum_{t=1}^{i}(X_{tj}-Z_{tj})$$

$$=\sum_{i=1}^{m}\sum_{j=1}^{n}b\beta_j f_j\sum_{t=1}^{i}(X_{tj}-Z_{tj})$$

$$=\sum_{j=1}^{n}b\beta_j f_j\sum_{i=1}^{m}\sum_{t=1}^{i}(X_{tj}-Z_{tj})$$

$$=\sum_{j=1}^{n}b\beta_j f_j\sum_{i=1}^{m}(m-i+1)\ [X_{ij}-Z_{ij}]$$

$$=\sum_{i=1}^{m}\sum_{j=1}^{n}(m-i+1)b\beta_j f_j X_{ij}-\sum_{i=1}^{m}\sum_{j=1}^{n}(m-i+1)b\beta_j f_j Z_{ij}$$

j plant at off-peak time in year i.

8. Now the complete linear programming model can be presented as follows:
Minimize

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \hat{c}_{ij} X_{ij} - \hat{d}_{ij} Z_{ij} + \hat{e}_{ij} Y_{ij} \qquad (6)$$

subject to

$$\sum_{j=1}^{n} \beta_j \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj}) \right] \geqq E_i \qquad \text{for all } i \qquad (1)$$

$$\sum_{j=1}^{n} Y_{ij} \geqq D_i \qquad \text{for all } i \qquad (2)$$

$$Y_{ij} \leqq \alpha_j \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj}) \right] \qquad \text{for all } i \text{ and } j \qquad (3)$$

$$\sum_{i=1}^{m} X_{ih} \leqq M_h \qquad \text{for all } h \qquad (4)$$

$$\sum_{i \in q} \sum_{j=1}^{n} K_{ij} X_{ij} \leqq K_q \qquad \text{for all } q \qquad (5)$$

$$X_{ij} \geqq 0, \quad Z_{ij} \geqq 0, \quad Y_{ij} \geqq 0.$$

II. A Linear Programming Model with Certainty and Gestation Period: Model 2

(1) Model 1 has been formulated under the assumption of immediate construction. However, it is more realistic to assume that there exists a gestation period for the construction of each type of plant.

(2) Let l_j be the gestation period for the construction of type j plant. Then the peak demand constraint (1) in Model 1 should be changed as follows:

$$\sum_{j=1}^{n} \beta_j \left(A_j + \sum_{t=1}^{i-l_j} X_{tj} - \sum_{t=1}^{i} Z_{tj} \right) \geqq E_i \qquad \text{for } i > l_j \qquad (7)$$

$$\sum_{j=1}^{n} \beta_j \left(A_j - \sum_{t=1}^{i} Z_{tj} \right) \geqq E_i \qquad \text{for all } i \leqq l_j$$

That is to say, only type j plants whose constructions are started l_j years before year i will be available for meeting peak demand in year i.

(3) Also, the capacity constraint (3) in Model 1 will be changed as follows:

$$Y_{ij} \leqq \alpha_j \left[A_j + \sum_{t=1}^{i-l_j} X_{tj} \sum_{t=1}^{i} Z_{tj}\right] \qquad \text{for } i > l_j \qquad (8)$$

$$Y_{ij} \leqq \alpha_j \left[A_j - \sum_{t=1}^{i} Z_{tj}\right] \qquad \text{for } i \leqq l_j.$$

(4) The budget constraints also require some changes, since the construction costs will be distributed across the gestation period. Let k_{ij}^{i+l} be the construction cost occurred in year $i+l$ for type j plants whose constructions are started in year i, Then, the budget constraints are

$$\sum_{i+l\varepsilon q} \sum_{j=1}^{n} k_{ij}^{i+l} X_{ij} \leqq K_q \qquad \text{for all } q \qquad (9)$$

(5) The hydro potential constraints and objective function will be the same as those in Model 1. However, since the construction costs will be distributed across the gestation period, the construction costs occurring after year i should be discounted back to year i in computing c_{ij} for the objective function.

III. A Linear Programming Model with Uncertainty in Supply: Model 3

(1) In this model, supply is considered to be uncertain by assuming that α_j and β_j are uncertain, whereas demand is assumed to be certain. Of course, demand is also uncertain in the electric power industry. Then, logically, we have to combine both uncertainties. By doing this we would obtain a problem which is convex but non-linear. In this analysis, however, uncertainties in demand will be dealt with by sensitivity analysis using two different demand projections, an optimistic projection and a less-optimistic projection. There are two reasons for doing this. One is to keep the model

linear and the other is that it is not possible to get a very reliable probability distribution of future demand for electric power in Korea. The idea of chance-constrained programming will be used in dealing with uncertainties in supply. With this approach, we obtain a certainty-equivalent linear programming model. Although zero gestation period is assumed here for the sake of simplicity, it is not difficult to generalize this model.

(2) We have the peak demand constraints

$$\sum_{j=1}^{n} \beta_j \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right] \geqq E_i \quad \text{for all } i \qquad (1)$$

in Model 1. Since β_j is assumed to be uncertain, constraint (1) in Model 1 should be changed to

$$Pr\left\{\sum_{j=1}^{n} \beta_j \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right] \geqq E_i\right\} \geqq \Pi 1 \qquad \text{for all } i \qquad (10)$$

where Π_1 represents the desired probability levels of meeting the peak demand. Suppose β_j has a normal distribution with known mean, $\bar{\beta}_j$, and variance, δ_j^2. From the laws of normal distribution, we have

$$Pr\left\{\bar{\beta}_j - \lambda(\Pi_1)\delta_j \leqq \beta_j\right\} = 1 - \phi(\lambda) = \Pi_1$$

where $\lambda(\Pi_1)$ represents the normal deviate and $\phi(\lambda^\circ)$ represents the area under the normal density function (i.e., normal distribution function). Hence, constraint (10) will be fulfilled with probability Π_1 if the normal deviate, λ, is set at the level corresponding to Π_1 in

$$\sum_{i=1}^{n} [\bar{\beta}_j - \lambda(\Pi_1)\delta_j] \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right] \geqq E_i \qquad \text{for all } i \qquad (11)$$

Since λ is tabulated for any given Π_1, (11) is a linear inequality for given Π_1 Thus (11) is the certainty constraint which replaces the stochastic constraint (10).

(3) By using the same logic, constraint (3) in Model 1 should be replaced by constraint (12) under the assumption that α_j is normally

distributed with known mean, $\bar{\alpha}_j$ and variance $\sigma^2{}_j$. The certainty-equivalent constraints are

$$Y_{ij} \leqq [\alpha_j - \lambda(\Pi_2)\sigma_j] \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right]$$

for all i and j (12)

where Π_2 represents the desired probability level of meeting the off-peak demand.

(4) Hence, the uncertainties in α_j force us to reformulate the constraints and the objective function as follows:

Minimize

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \left[c_{ij} X_{ij} - d_{ij} Z_{ij} + af_{ij} Y_{ij} + b(\beta_j - \lambda(\pi_1)\delta_j)\right.$$

$$\left. f_{ij} \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right] \frac{1}{(1+r)^{i-1}} \qquad (6')$$

subject to

$$\sum_{j=1}^{n} [\bar{\beta}_j - \lambda(\pi_1)\delta_j] \left[\mathrm{A}_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right] \geqq E_i$$

for all i (11)

$$\sum_{j=1}^{n} Y_{ij} \geqq D_i \qquad \text{for all i} \qquad (2)$$

$$Y_{ij} \leqq [\bar{\alpha}_j - \lambda(\pi_2)o_j] \left[A_j + \sum_{t=1}^{i} (X_{tj} - Z_{tj})\right]$$

for all i and j (12)

$$\sum_{i=1}^{m} X_{ih} \leqq M_h \qquad \text{for all h} \qquad (4)$$

$$\sum_{i\epsilon q} \sum_{j=1}^{n} k_{ij} X_{ij} \leqq Kq \qquad \text{for all q} \qquad (5)$$

$$X_{ij} \geqq 0 \quad Z_{ij} \geqq 0 \quad Y_{ij} \geqq 0.$$

Here we obtain a certainlty-equivalent linear programming problem.

IV. A Mixed Integer Programming Model with Uncertainty and Economies of Scale: Model 4

(1) The most critical consequence of a linear programming model is that it eliminates from this model the factors of economies (or disecomies) of scale. Hence, it is desirable to have a model which takes care of economies of scale without significantly affecting the tractability of the model. For this purpose, a finite number of different sizes of standardized plants are considered as different techniques. This modification requires us to reformulate the problem in terms of a mixed integer program.

(2) Decision variables:

W_{ijk}=number of size k plant in the category of type j plant (type jk plant) to be constructed in year i

V_{ijk}=number of type jk plants to be retired in year i

Y_{ijk}=capacity of type jk plant utilized for off-peak demand in year i.

W_{ijk} and V_{ijk} are restricted to be non-negative integers while Y_{ijk} can be any non-negative numbers.

(3) Peak demand constraints:

Let β_{ik} be β_j times unit size of type jk plant. Assuming that β_{jk} has a normal probability distribution with known mean, $\bar{\beta}_{jk}$ and variance $\delta^2{}_{jk}$. the peak demand constraints can be written

$$\sum_{j=1}^{n}\sum_{k=1}^{kj}[\beta_{jk}-\lambda(\Pi_1)\ \delta_{jk}]\left[B_{jk}+\sum_{t=1}^{i}(W_{tjk}-V_{tjk})\right]$$

$$\geqq E_i \qquad \text{for all i} \qquad (13)$$

where k_j represents number of standardized size in the category of type j plant and B_{jk} represents the existing units of type jk plant before the planning horizon.

(4) Off-peak demand constraints:

$$\sum_{j=1}^{n}\sum_{k=1}^{kj} Y_{ijk} \geqq D_i \qquad \text{for all i} \qquad (14)$$

(5) Capacity constraints:

Denoting α_{jk} as α_j times unit size of type jk plant and assuming that α_{jk} has a normal probability distribution with known mean $\bar{\alpha}_{jk}$ and variance σ^{2jk}, the capacity constraint for each type of plant becomes

$$Y_{ijk} \leqq [\bar{\alpha}_{jk} - \lambda(\Pi_2)\ \sigma_{jk}] \left[B_{jk} + \sum_{t=1}^{i} (W_{tjk} - V_{tjk})\right]$$

for all i and i and k and j (15)

(6) Hydro potential constraints:

$$\sum_{i=1}^{m} W_{ihk} \leqq M_{hk} \qquad \text{for all h and k} \qquad (16)$$

(7) Budget constraints:

$$\sum_{i\epsilon q} \sum_{j=1}^{n} \sum_{k=1}^{kj} g_{ijk}\ W_{ijk} \leqq K_q \qquad \text{for all q} \qquad (17)$$

where g_{ijk} represents the amount of capital required to construct one unit of type jk plant in year i.

(8) Objective function:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{kj} \Big[c_{ijk}\ W_{ijk} - d_{ijk}\ V_{ijk} + af_{ijk}\ Y_{ijk}$$

$$+ b(\bar{\beta}_{jk} - \lambda(\Pi_1)\delta_{jk})\ f_{ijk} \sum_{t=1}^{i} (W_{tjk} - V_{tjk})\Big] \frac{1}{(1+r)^{i-1}}$$

(18)

IV. TESTS AND SENSITIVITY ANALYSES

I. General Considerations

1. Alternative techniques

In this analysis, the following six groups of homogenous plants are considered;

(1) Gas turbine

(2) Oil-fired thermal plant

(3) Korean-anthracite coal-fired thermal plant

(4) Hydropower plant Group I

(5) Hydropower plant Group II

(6) Nuclear power plant.

The hypothesis of homogeneous plants simplifies the problem greatly so that we can solve it without much difficulty. In fact, the hypothesis of homogenous plants is not realistically unacceptable except for the case of hydropower plants. Each hydropower site exists with its own peculiar physiognomy. Thus, in general, hydropower belogs to the realm of prototype selection rather than group selection. The programming techinques are capable of including some of this situation by multiplying the number of groups. In this analysis, however, only two groups·· 20 MW or above and below·· 20 MW of homogeneous hydropower plants are assumed for the following reasons:

(1) The essential hydrological data for individual hydro sites are not available at this time.

(2) The hydro sites in Korea have many characteristics in common, since the weather and the characteristics of the four rivers are very much the same.

Obviously some of the diversity of the hydro sites should be incorporated into the analysis as the data becomes available. I think that their injection into the model need not complicate the calculation very much.(1)

2. Costs

Table 1 shows the estimated costs of the different techniques. Capital costs, maintenance costs and fuel costs are explicitly considered, Maintenance costs are assumed to be proportionate to capital costs for a given technique and independent of the level of operation. Operating costs other than fuels are disregarded. Since some variability is inevitable in estimating costs, the

(1) The upper-bound technique will handle this problem efficiently.

figures in Table 1 are subject to several qualifications. The tests have been carried out on the basis of the cost figures in Table 1 unless otherwise specified. Sensitivity has been tested whenever it appears to be necessary.

It is comparatively easy to predetermine the cost of equipment per KW for a given type of conventional thermal plant of a certain size. The cost of shipping and local installation can also be estimated without much

<Table 1> Cost Estimates

Technique	Capital Costs (KW)	Annual Maintenance Costs (KW)	Fuel Costs (KWH)
Gas turbine	$ 90	$ 1.66	10 mills
Oil-fired thermal	138	2.76	5 〃
Coal-fired thermal	160	4.00	4 〃
Hydropower group I	340	3.40	0 〃
Hydropower group II	380	3.80	0 〃
Nuclear power	250	5.00	2.5 〃

difficulty. It is difficult to predetermine the capital cost of a nuclear power plant, since the technical knowledge in the field is new and still somewhat uncertain. The recent experience indicates that the capital costs cover a range extending from $ 180～300 per KW of installed capacity, with an electrical output of 300～500 MW, and with boiling and pressurized water reactor appearing as the leading contenders. It is more difficult to estimate the capital cost of a hydropower plant. It varies from one site to another with topographical and hydrological features. As mentioned earlier, the hydro sites in Korea have many characteristics in common and no site seems to be particularly distinguished from other sites. This greatly reduces the significance of the variability of capital costs in hydropower plants. The capital costs of hydropower plants completed recently or under construction cover a range extending from $ 300～370 per KW of installed capacity.

Admitting some variability of the costs, the calculations are repeated under a number of different assumptions about the costs.

3. Some considerations on economies of scale

The linear programming formulation assumes that there are no economies or diseconomies of scale in the electric power industry. However, it seems to be generally agreed that(dis) economies of scale are important in the electric power industry, It is often thought that diseconomies of scale exist in the development of hydropower since earlier development tends to exhaust more economic sites. This turns out to be not quite correct because the choice is also limited, during the early stages, by the scale of demands and accessibility to intrinsically less economic sites. For example, in Taiwan the average capital cost per KW of plant installed was about $378 prior to 1946. However, the average capital cost fell to $259 in the post-war period.(2) Since only a few hydro sites have been developed in Korea, this kind of data is not obtainable. In Korea, it is agreed that the development of hydro sites whose potential capacity is less than 20 MW will require a higher capital cost per KW than that of 20 MW or above.(3)

Since this problem of diseconomies of scale in hydropower is already considered by introducing two different groups of homogeneous plants, this section is concerned with the problem of economies of scale in conventional thermal plants and nuclear power plants.

There have been a number of attempts to evaluate the importance of economies of scale in the power industry.(4) Johnston concludes that, "...the economies of scale in electricity generation can be fully exploited by firms of quite medium size" and "...apart from the steep initial fall, this curve

(2) The construction cost is adjusted to the 1963 price by applying price index and then converted into U.S. $ equivalent with an exchange rate of N.T. 40.1 to U.S. $1.00. UNECAFE, *Economic Bulletin*, Bangkok, Thailand, December 1965, p. 36.

(3) Korea Electric Power Industry Survey Team, *Korea Electric Power Survey*, Vol. I, p. 128.

(4) For example, J. Johnston, "Statistical Cost Functions in Electricity, Supply," *Oxford Economic Papers*, February 1952, pp. 68—105.

R. Komiya, "Technological Progress and the Production Function in the United States Steam Power Industry", *The Review of Economics and Statistics*, May 1962, pp. 156—166.

Y. Barzel, "Productivity in the Electric Power Industry, 1929—1955. "*The Review of Economics and Statistics*," November 1963, pp. 395—408.

(i.e. average capital cost curve) approximates to a horizontal straight line over the major part of the range of possible outputs."(5) Komiya finds that, "...in steam power generation the scale effects is a far more important factor in the process of technological progress than either factor substitution or pure technological change."(6) The economies of scale in nuclear power are considered to be more important than in conventional steam power. It is characteristic of nuclear power that its competitive position improves as the size of plant increases.

As shown in Model IV, the model most appropriate for considering economies of scale is a model of the mixed integer type. It is not difficult to formulate a mixed integer programming model, but it is very difficult to solve it when a large number of integer variables are used.

In this analysis, capital costs for each technique are obtained by presupposing the range of capacity to be constructed and by assuming that constant return to scale is applicable within that range of capacity.(7) For conventional thermal plants, it is assumed that the capacity 100 MW～300 MW will be constructed, This range is chosen on the basis that additional capacity required in each planning period is big enough to accommodate a number of plants with capacity bigger than 100 MW and that, in medium size thermal plants of this capacity, economies of scale in electricity generation can be fully exploited. The range of 300 MW～500 MW is considered to be appropriate for nuclear power. The nuclear power plants whose capacity is less than 300 MW are not considered because they will not be competitive to conventional thermal plants of that range during the planning horizon in Korea. Upper limit of the capacity of a nuclear plant is set by security

(5) Johnston, *op. cit.*, p. 99.
(6) Komiya, *op. cit.*, p. 166.
(7) To presuppose the ranges of size of plants leads us to the problem of fractional plants for each planning period when we solve the linear programming model. Since the fractional plants will be a very small proportion of total capacity expansion for each planning period, neglect of this problem should not be unacceptable.

reasons. Since the larger the plant is the more severe are the economic consequences of an unscheduled shutdown, it is generally agreed that the proportion of total capacity represented by a single plant should not exceed a relatively small fraction.[8] There is evidence that utility companies in the United States are experiencing a higher than expected rate of forced shutdown in the operation of their newest, largest and most sophisticated conventional plants.[9] Nuclear power is new technology and its dependability is not well evaluated yet. Moreover, the rate of failure might be higher in underdeveloped countries because of the absence of nuclear skills. It appears that the power market in Korea after the second planning period will be sufficiently large to accommodate the 500 MW size of nuclear power plant without seriously endangering system reliability.

4. α and β

(1) Thermal and nuclear power

A certain percentage of installed capacity of the system should be out of service for regular maintenance and unexpected failures. Hence, total installed capacity cannot be taken to be available for meeting the demands for electric power. α_j and β_j represent the ratios of the available capacity to installed capacity of type j plant at off-peak time and peak time, respectively. For the following tests, α and β for thermal and nuclear power plants are assumed to be 0.75 and 0.85, respectively. The α is assumed to be lower than β by assuming that regular maintenance could be scheduled to be done mainly during the off-peak period. In Korea, no reliable data are available for estimating α and β separately. The average plant factor of three thermal plants constructed in 1957 was approximately 0.77 during 1958—1965.[10] This figure can be taken to represent the

(8) In general, 10 to 15% has been suggested.
(9) See J.H. Horgerton, "The Arrival of Nuclear Power," *Scientific American*, February 1968, p.27.
(10) Source: Korea Electric Company, *Statistical Yearbook*, Seoul, Korea, 1966.

technically feasible plant factor since the plants have always been fully utilized during that period. Assuming that β is equal to 0.85[11] and that the peak time accounts for one-sixth of a year, α is estimated to be 0.75.[12]

(2) Hydropower

The dependable capacity of a hydropower plant is very uncertain unless it has a sufficiently big reservior since the availability of a hydropower plant largely depends on the inflow of water.[13] Hence, the availability of a hydropower plant has to be determined on the basis of hydrological data over a considerable length of time. This type of hydrological data is not available yet in Korea. During 1958—1965, the average plant factor of existing hydro plants was 0.54.[14] For the tests, the figure 0.54 is used to represent both α and β for hydropower in the certainty model. For the tests of the uncertainty model, α and β are reduced to 0.41 so that 90 percent guarantee can be attained.

5. Demand

Relatively accurate demand projections are an essential prerequisite for a sound development plan for electric power. In Korea, however, there are a number of difficulties in obtaining accurate demand projections. The main difficulties are the lack of data and the rapid structural changes of the economy. Hence, power demand projections provide room for a wide range of disagreement and error.

For the analysis, the demand for electric power(1967—1976) is based on the projection made by the Korea Electric Company in September 1967. The consumers are classified as lighting, small power (under 500 KW

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(11) It is a general practice in the electric power industry to assume the availability of the range of 80—90% of installed capacity.

(12) Since $\frac{1}{6}0.85+\frac{5}{6}\alpha=0.77$, $\alpha=0.75$.

(13) By providing a reservoir, it would be possible to increase the availability of a hydropower plant. But this would require an additional cost. Hence, the determination of optimum size of reservoir to be built for a hydropower plant is another interesting problem to be studied.

(14) Source: Korea Electric Company, ***Statistical Yearbook***, Seoul, Korea, 1966.

demand), larger power (500 KW or over) and agricultural power. The built-up projection method is used to forecast larger power and agricultural use. For the estimation for lighting and small power, the number of houses electrified[15] and the index of industrial production are used as explanatory variables. The following basic assumptions are made for the

<Table 2> **Demand Projection**

	Annual Demand (GWH)	Peak Demand (MW)	Off-Peak Demand (MW)	Average annual growth rate in each planning period (%)
1967	5,130	878.4	527.0	
1968	6,609	1,131.6	679.0	
1969	8,391	1,436.8	862.1	28.1
1970	10,643	1,822.2	1,093.3	
1971	13,380	2,291.1	1,374.7	
1972	16.206	2,775.0	1,665.0	
1973	19,000	3,253.4	1,952.0	
1974	21,762	3,726.4	2,235.8	15.2
1975	24,493	4,194.0	2,516.4	
1976	27,194	4,656.5	2,793.9	
1977	29,913	5,122.0	3,072.6	
1978	32,828	5,622.0	3,372.6	
1979	35.744	6.122.0	3,672.6	8.8
1980	38,668	6,622.0	3,972.6	
1981	41,488	7,122.0	4,272.6	

Footnotes: (a) GWH=million KWH

(b) The peak demand and the off-peak demand are estimated from the annual demand on the basis of the following assumptions:

(1) Load factor=0.666

(2) Peak hours=4 hours a day; Off-peak hours=20 hours a day; Number of hours in a year=8,760

(3) Peak demand $(KW)=\frac{\text{Annual Demand (KWH)}}{8,760}\times\frac{1}{0.66}$

(4) Off-peak demand $(KW)=\frac{(\text{Annual Demand}-\text{Peak demand}\times 1460)}{7,3000}$

(c) The demand for 1977-1981 is estimated by assuming annual growth rate of 8.8% during the period.

Source: Korea Electric Company, ***An Outline of the Ten Year Power Development Program*** (1967—1976),Seoul, Korea, September 1967.

(15) The rate of electrification in Korea is only 29.8% in 1966. Hence, the number of houses electrified represents the target of the government to increase the number of houses electrified in the future.

projection:

(1) The GNP will grow at rates of 10 percent a year during the second five-year economic development plan (1967—1971) and 7 percent a year during the third five-year economic development plan (1972—1976).

(2) The rates of electrification will be increased to 45.4 percent and 80 percent at the end of 1971 and 1976, respectively.

According to the projection, it is estimated that the demand for electric power would grow at the average rate of 28.1 percent a year during 1967—1971 and 15.2 percent a year during 1927—1976, (See Table 2) It is assumed that the growth rate of the demand for electric power will slow down to about 8.8 percent a year during 1977—1981.

Demand projection is usually stated in terms of annual generation of electric power. But to satisfy the consumers' need all the time, peak demand conditions must also be looked into, since it is the peak demand which determines the required capacity, The peak demand can be obtained by applying estimated load factors[16] to the annual demand.

For the projection, the load factor is taken to be constant during the planning horizon by assuming that the structure of power demand would not change greatly. (See the footnotes in Table 2)

II. Test no. 1—Sensitivity to Discount Rate

The first test is designed to investigate the competitive position of various techniques at different discount rates. Since each technique requires different capital and fuel costs, it is not unreasonable to expect that the discount

(16) Load factor$=\frac{\text{Average Demand}}{\text{Peak Demand}}$. The load factor is a rough indicator of the structure of the power demand in an economy. It is desirable to have a high load factor so that generating facilities can be operated steadily over time. Consequently, there is the possibilty of designing a tariff structure which encourages the use of power during the off-peak period. The load factor will also change as the structure of an economy changes. For instance the increase in the proportion of industrial demand to total demand tends to raise the load factor.

rate is indeed of crucial importance in the choice of techniques. For this test, no budget constraint is considered. The results of the test are summarized in Tables 3 and 4. In Table 3 the construction costs of coal-fired thermal plants and oil-fired thenmal plants are taken to be $ 160 and $ 136 per KW of installed capacity, respectively, whereas the corresponding figures in Table 4 are 152 and 129, respectively.

The results indicate that the choice of techniques is very sensitive to the discount rate. The following generalization, with some qualifications in mind, could be derived.

(1) Disregarding the benefits other than power generation from construction of hydropwer, the development of hydropower group I for base loads is justified at a discount rate of 7 percent or below, while the hydropower group II (below 20 MW) is not competitive to coal-fired thermal plants at present coal price if we accept 7 percent as the appropriate discount rate. However, if the construction cost of coal-fired thermal plants

<Table 3> Choice of Techniques at Various Discount Rates

Loads	Discount Rate		
	(5%)	(7%)	(9%)
Base loads[a] Peak loads[b]	Hydropower I & II Nuclear power Oil-fired thermal	Hydropower I Coal-fired thermal Oil-fired thermal	Coal-fired thermal Oil-fired thermal

<Table 4> Choice of Techniques at Various Discount Rates

Base loads Peak loads	Hydropower I Nucler power Oil-fired thermal	Coal-fired thermal Oil-fired thermal	Coal-fired thermal Oil-fired thermal

Footnotes:

(a) Plants built for base loads will be utilized at off-peak time as well as peak time.

(b) Plants built for peak loads will be utilized for meeting peak demand only.

(c) The potential capacities of hydropower group I and group II are limited to 1,040 MW and 560 MW, respectively.

(d) Construction costs of conventional thermal plants:

	Table 3	Table 4
Coal-fired thermal	$ 160	$ 152
Oil-fired thermal	136	129

is taken to be $ 152[17] instead of $ 160 per KW of installed capacity, the hydropower group I is also not competitive with coal-fired thermal plants at a 7 percent discount rate as shown in Table 4. Of course, the validity of this generalization is restricted mainly because of the variability of hydro sites and the benefits other than power generation. The detailed evaluation of each hydro site must be carried out before a final decision is made,[18] Since the potential capacity of hydropower group I is limited, any development of hydropower should be supplemented by either coal-fired thermal plants or nuclear power or both.

(2) At a discount rate higher than 7 percent, coal-fired thermal plants seem to be dominant for base loads, Nuclear power is competitive at a discount rate of 5 percent or below, which is not likely to be justified in Korea. As already indicated, however, the capital cost of nuclear power is still very uncertain. Thus, if the capital cost of nuclear power can be taken as $ 225 per KW of installed capacity, it becomes competitive for base loads even at a 9 percent discount rate. It is perhaps safe to say that nuclear power is not competitive with coal-fired thermal plants at reasonable discount rates unless a considerable reduction of the construction cost is obtained by technical progress which we shall discuss later.

<Table 5> Coal-Fired Thermal vs. Nuclear Power Base Loads

Capital Costs (KW)		Discount Rate		
		(5%)	(7%)	(9%)
Coal	$ 160	Nuclear	Coal	Coal
Nuclear	250			
Coal	160	Nuclear	Nuclear	Nuclear
Nuclear	225			
Coal	152	Nuclear	Nuclear	Nuclear
Nuclear	225			

(17) This figure may be justified if the most of the coal-fired thermal plants will be built in the unit size of 200 MW to 300 MW.

(18) This is what the French economists call the "marginal problem."

(3) The competitive position of oil-fired thermal plants for peak loads is so dominant that it is insensitive to the discount rate.

(4) It is discovered that there will be no retirement of plants during the planning horizon, because the costs of maintenance and operation of existing plants are less than the capital cost and maintenance and operation expenses of even the lowest cost type of techniques for peak use. When the old plants become so obsolete that they are no longer reliable, or the cost of maintaining them becomes excessive, it will be economical to replace them with new plants. The retirement of the existing plants during the planning horizon is not economical since the existing plants in Korea are all relatively new.

(5) Roughly, a 7 percent discount rate seems to be critical. If the decision-makers think that socially correct discount rate is higher than 7 percent, their choice must be conventional thermal plants, i.e., coal-fired thermal plants for base loads and oil-fired thermal plants for peak loads. On the other hand, if the discount rate could be properly regarded as lower than 7 percent, some hydropower and nuclear power could be developed for base loads unless such alternatives are restricted by other reasons such as budget constraints.

So a crucial difficulty rests on the choice of an appropriate discount rate to be used. Some people think that the rates of interest in many under-developed countries are relatively high sometimes as high as 10, 12 and 15 percent. However, even if this were true, it does not necessarily mean that such a high discount rate should be taken as the socially appropriate rate in evaluating alternative techniques in public utilities such as electric power and transportation. Objections to using the market rate of interest as a discount rate are based on the fact that this rate does not reflect the socially correct discount rate because of the existence of market imperfections, divergences between private and social costs, the existence of extra-economic values, and the dependence of the market rate upon the existing distribution of wealth and talents. These objections are particularly valid in under-developed countries where the above factors are significant.

Then the choice of discount rates, it can be argued, is really a matter of value judgment and cannot be done in terms of a precise criterion. The very nature of the problem makes it partly a political decision, although the market rate is obviously one of the important factors which will be take into account in actual decision-making. appropriate choices unless they are restricted by other reasons.

III. Test No. 2 ·· Impacts of Budget Constraints

In order to see the impacts of fixed budget on the choice of techniques it is assumed that the amount of capital available for power development is fixed for each five-year planning period.

For these tests, the budget constraints are obtained from the ten-year power development program and extended to 15 years by adding comparable amounts of capital for the third planning period. Table 6 shows the amount of capital budgeted for power development for each five-year planning period.

<Table 6> Capital Budget for Power Development

Planning Period	Budget (in thousand U.S. dollars)
1967~1971	427,896
1971~1976	595,779
1977~1981	625,000[a]

Footnotes; (a) This figure is obtained on the assumption that the allocation of investment funds should be proportionate to the capacity expansion required for each planning period.

Source; Korea Electric Company, *An Outline of the Ten-Year Power Development Program* (1967~1976), Seoul, Korea, September 1967.

As mentioned earlier, however, approximately half of the investment funds is supposed to come from foreign sources. It is hardly convincing to assume that all the amount budgeted can actually be obtained from foreign countries. Difficulty also exists in providing local funds. From past experience, the investment budget has always been, at best, the expression of desired level and actual investment has been far less than the budget[19]

In order to consider this uncertainty of the available capital for the power development, the test has been repeated under different levels of availability of the budget, i.e., 100, 80, 70 and 60 percent of the budget.

First, let us look at the impact of budget constraints on the choice of techniques of various discount rates. Table 7 is obtained by assuming that 80 percent of the budget will be actually available. The results are quite instructive. By looking at the marginal value of capital, it will be immediately

<Table 7> Optimum Capacity Expansion by Techniques Under Fixed Budget Constraints

(Unit : mw)

Discount Rate	Periods	Oil-fired thermal	Coal-fixed thermal	Hydropower I	Nuclear Power	Total	Marginal value of capital
5%	1967～1971	856	1,035	177	—	2,068	0.207
	1972～1976	909	1,731	223	—	2,863	0.115
	1977～1981	939	1,794	246	—	2,979	0.046
	Total	2,704	4,560	636	—	7,910	
	%	34.2	57.7	8.1	—	100.0	
7%	1967～1971	856	1,035	177	—	2,068	0.025
	1972～1976	909	1,731	223	—	2,863	0.008
	1977～1981	928	1,971	—	—	2,899	0.000
	Total	2,693	4,737	400	—	7,830	
	%	34.4	60.5	5.1	—	100.0	
9%	1967～1971	841	1,165	—	—	2,006	0.000
	1972～1976	890	1,892	—	—	2,782	0.000
	1977～1981	928	1,971	—	—	2,899	0.000
	Total	2,659	5,028	—	—	7,687	
	%	34.6	65.4	—	—	100.0	

Footnote: It is assumed that 80% of the budget will be actually available, i.e., the maximum amount of capital available for each planning period is as follows (in thousand U.S. dollars);

1967～1971	342,317
1972～1976	476,623
1977～1981	500,000

(19) A typical example is the fact that during the first five-year economic development planning period (1961～1966), only 38 percent of the original budget was actually invested. This resulted in a severe shortage of power supply in 1967 and the reintroduction of power rationing which had been lifted in 1964.

concluded that the lower the discount rate, the greater the impacts of budget constraints on the choice of techniques. At a 9 percent discount rate, the budget constraints are no longer active. This finding is not unexpected, since the competitive position of a less capital expensive technique will strengthen as the discount rate goes up. The results also show us that the introduction of budget constraints makes the choice of techniques less sensitive to discount rates by reducing the area of feasible solutions. Even at lower discount rates(5 percent or below) the combination of hydro and nuclear power for base loads is eliminated and the development of hydropower is greatly discouraged due to the lack of available funds. Regardless of the discount rate chosen, the development of hydropower is limited to less than 9 percent of total capacity expansion during the planning horizon. Consequently, the choice of techniques in the range of 5 to 9 percent turns out to be very much similar.

Next, it is interesting to notice the relationships between the availability of budget and the choice of techniques. Table 8 is obtained by varying the level of availability of budget at a 7 percent discount rate. At 70 percent availability, neither nuclear nor hydro power is developed. If we assume 60 percent availability, there would be no feasible solution unless we include a considerable amount of gas turbine which is the least capital expensive but the most fuel expensive technique.

These results suggest to us, that, under the existence of imperfection of capital market and political influence on the allocation of budget, the introduction of budget constraints is not only justified but also necessary. When decision-makers tend to choose a lower discount rate in favor of capital intensive fuel-saving techniques, their intention can actually be realized if there exists a feasible solution with the limited funds available. Under tight budget constraints, the choice of a lower discount rate on the basis of a "conservationist" philosophy would not bring about a choice of

<Table 8> **Optimum Capacity Expansion by Techniques under Different Level of Budget Availability** (Unit: MW)

Budget	Periods	Gas turbine	Oil-fired thermal	Coal-fired thermal	Hydro-power I	Nuclear power	Total	Marginal value of capital
	1967—1971	—	887	775	538	—	2,200	$0.020
	1972—1976	—	890	1,576	502	—	2,968	0.000
100%	1977—1981	—	928	1,971	—	—	2,899	0.000
	Total	—	2,705	4,322	1,040	—	8,067	
	%	—	33.5	53.6	12.9	—	100.0	
	1967—1971	—	856	1,035	177	—	2,068	0.025
	1972—1976	—	909	1,731	223	—	2,863	0.008
80%	1977—1981	—	928	1,971	—	—	2,899	0.000
	Total	—	2,693	4,737	400	—	7,830	
	%	—	34.4	60.5	5.1	—	100.0	
	1967—1971	—	887	1,119	—	—	2,006	0.362
	1972—1976	—	1,174	1,608	—	—	2,782	0.251
70%	1977—1981	—	1,108	1,791	—	—	2,899	0.106
	Total	—	3,169	4,518	—	—	7,687	
	%	—	41.2	58.8	—	—	100.0	
	1967—1971	759	459	788	—	—	2,006	0.768
	1972—1976	1,047	603	1,132	—	—	2,782	0.620
60%	1977—1981	857	1,212	830	—	—	2,899	0.231
	Total	2,663	2,274	2,750	—	—	7,687	
	%	34.6	29.6	35.8	—	—	100.0	

Footnote: 7% discount rate is used.

techniques which is much different from the one obtained at a higher discount rate, unless it is accompanied by an increase of available funds.

IV. Test NO. 3··Impacts of Technical Progress

There is no question about the fact that technical progress has greatly contributed to reduce both the labor and capital requirement per KW of installed capacity and the fuel requirement per KWH generated in the electric power industry. It is likely that such technical progress will, more or less, continue in the future. If technical progress is sufficiently predictable, it would not be difficult to incorporate it into the programming model.

Technical progress, in general, is a mixture of several factors such as economies of scale, improvements in the quality of the inputs, and pure technological change. As far as conventional thermal plants are concerned, technical progress has followed, roughly, a smooth trend and there have been many attempts to measure the relative contributions of the above factors as well as overall technical progress. Although such attempts have contributed to better understanding of the nature of technical progress in conventional thermal plants, it does not mean that the technical progress is sufficiently predictable. In practice, we have only a very vague notion about technical progress in the future. A further difficulty may arise as a result of the fact that the course of technical advance is not independent of the choice of techniques today. A common excuse for neglecting this problem is that in the initial stages of the development of underdeveloped economies, techniques already developed in the advanced countries may be used.

There are some conservative views as to technical progress in conventional thermal plants. J. Ullmann indicates that

> Many of the economies found effective in the past have now been exhausted or yield little changes. For example, pressure of 6000 psi are now feasible and relatively little is to be gained from going even higher into the super-critical range. Temperatures now used are close to the metallurgical limits of conventional construction materials. Labor is now at a minimum and the automation systems now being offered for electric power systems must be justified on the basis of fuel economies and avoidance of major breakdowns rather than labor saving. The capitalized value of more saved labor would be insufficient under present conditions to pay for any significant new control system.[20]

(20) J.E. Ullman, "Economics of Nuclear Power," *Advances in Nuclear Science and Technology*, edited by E.J. Henly and H. Kouts, 1962, pp. 234—235.

It seems to me, however, this conservative view is not as applicable in the case of Korea as in the case of the advanced countries. The rapid expansion of the power market would make feasible to transfer many technological changes which have already been implemented in advanced countries.

The nature of technical progress in nuclear power is much more difficult to predict. Predictions as to the prospects of nuclear power have been made since Hiroshima. They have been characterized by periods of optimism and pessimism. In the last few years, nuclear power plants have shown a decisive market break-through in the United States.[21] However, the nature of technical progress is still unpredictable. While it is possible to make extrapolations of past developments, these are likely to be useless unless strongly qualified by a careful study of what events may result in substantial changes. It may be safe to say that technical progress in nuclear power would be faster than that of conventional power, since there are many identifiable potential improvements to be made in nuclear power.

Predictions as to technical progress in each technique is beyond the realm of this study. For the tests, some hypothetical assumptions are made in order to investigate the impacts of technical progress on the choice of techniques.

(1) As to conventional thermal power, two different rates of technical progress are assumed. One is no technical progress(pessimistic view) and the other is 2 percent a year(optimistic view).

(2) In determining the rates of technical progress in nuclear power, it is assumed that the rate of technical progress in nuclear power will be higher than the optimistic rate of technical progress in conventional power plants, but it would not reduce the capital and fuel costs less than half of present level during the planing horizon, The tests are repeated under three

(21) For a brief history of nuclear power development, see Hogerton, *op. cit.*

different rates of technical progress, i.e., 3, 4 and 5 percent.

(3) No technical progress is assumed for hydropower on the basis that any technical progress will be offset by diseconomies of scale.

Some of the results of the tests are summarized in Tables 9, 10 and Table 9 shows us optimum capacity expansion by techniques we should choose when we take optimistic view for technical advance in conventional power and pessimistic view for that in nuclear power. The results strongly indicate that even if we take the conservative view as to further technical advance in nuclear power(of course, it is still estimated to be higher than the optimistic one as to conventional power), nuclear power will dominate the power system from the second planning period. It shows, at discount rate 7 percent or below, the entire new addition of capacity to the power system in the third planning period should be nuclear power unless it is limited by budget constraints. In other words, the construction of some oil-fired thermal plants during 1977—1981, at discount rates 5 and 7 percent, is not due to its competitiveness but due to budget constraints. The increase of peak demand in that period will be met by using the oil-fired thermal plants and a part of the coal-fired thermal plants which will be freed from base use due to the introduction of nuclear power. At 9 percent discount rate, new addition of oil-fired thermal plants for peak loads is justified for the third planning period. As shown in Table 10, however, technical progress of 4 percent a year in nuclear power does not allow new addition of oil-fired thermal plants for peak loads even at 9 percent discount rate. If technical progress in nuclear power is assumed to be 5 percent a year, the entire addition of capacity after the first planning period should be nuclear power.

It is interesting to note in Table 11 that, in the first planning period, the addition of oil-fired thermal plants amounts to 1,382 MW or more than 2/3 of the capacity increase required in that period. Since the capacity

<Table 9> **Optimum Capacity Expansion by Techniques under Technical Progress** (Unit: MW)

Discount Rate	Period	Oil-fired thermal	Coal-fired thermal	Hydropower	Nuclear Power	Total
5%	1967—1971	1,016	830	247	—	2,093
	1972—1976	1,100	—	—	1,682	2,782
	1977—1981	139	—	—	2,760	2,899
	Total	2,255	830	247	4,442	7,774
	%	29.0	10.7	3.2	57.1	100.0
7%	1967—1971	861	995	233	—	2,089
	1972—1976	1,100	—	—	1,682	2,782
	1977—1981	139	—	—	2,760	2,899
	Total	2,100	995	233	4,442	7,770
	%	27.0	12.8	3.0	57.1	100.0
9%	1967—1971	841	1,165	—	—	2,006
	1972—1976	890	383	—	1,509	2,782
	1977—1981	928	—	—	1,971	2,899
	Total	2,659	1,548	—	3,480	7,687
	%	34.6	20.1	—	45.3	100.0

Footnotes: (a) No nuclear power construction is allowed during 1967—1971
(b) It is assumed that 80% of the budget will be actually available.
(c) Technical progress:
Conventional thermal power: 2% a year
Nuclear power : 3% a year

<Table 10> **Optimum Capacity Expansion by Techniques under Technical Progress** (Unit: MW)

Discount rate	Periods	Oil-fired thermal	Coal-fired thermal	Hydropower	Nuclear power	Total
9%	1967—1971	983	1,023	—	—	2,006
	1972—1976	749	—	—	2,033	2,782
	1977—1981	—	—	—	2,899	2,899
	Total	1,732	1,023	—	4,932	7,687
	%	22.5	13.3	—	64.2	100.0

Footnotes: (a) It is assumed that 80% of the budget will be actually available.
(b) Technical progress:
Conventional thermal power: 2% a year
Nuclear power : 4% a year

increase required for peak demand during the period is only 841 MW, it means that a considerable amount of oil-fired thermal plants are built for

<<Table V-11> **Optimnm Capacity Expansion by Techniques under Technical Progress** (Unit: MW)

Discount rate	Periods	Oil-fired thermal	Coal-fired thermal	Hydropower	Nuclear power	Total
9%	1967—1971	1,382	721	—	—	2,103[(a)]
	1972—1976	—	—	—	2,683	2,683
	1977—1981	—	—	—	2,899	2,899
	Total	1,382	721	—	5,582	7,687
	%	18.0	9.4	—	72.6	100.0

Footnotes: (a) 99 MW of excess capacity is provided.
(b) It is assumed that 80% of the budget will be actually available.
(c) Technical progress:
Conventional thermal power; 2% a year
Nuclear power : 5% a year

base loads even though they are not competitive to coal-fired thermal plants for base loads if we consider the first planning period only. The imlication of this fact is that if technical progress occurs, and is sufficiently predictable, there is an advantage permitting less capital expensive plants for short period use and, then, incorporating technical progress not long after they are made.

So far the results have shown that nuclear power will dominate the power system if a reasonable rate of technical progress is assumed. In reality, however, there are two important factors which will delay such dominance of nuclear power even if the optimistic rate of technical progress in nuclear power is attained.[(22)] One is the lack of capital available for power development and the other is a longer gestation period in nuclear power construction.

As mentioned earlier, one of the crucial bottlenecks for power development is the lack of capital. Tight budget constraints greatly discourage relatively capital expensive nuclear power development. Table 12 shows what the choice of techniques should be when the optimistic rate in nuclear power

(22) Here, I am not concerned with non-economic aspects of nuclear power development. Certainly there are many non-economic obstacles in the process of rapid expansion of nuclear power. These aspects will be discussed in the next chapter.

is expected, but only 60 percent of the budget is actually available for power development. Under this tight budget constraint, construction of nuclear power is restricted to 3,250 MW or 42 percent of total capacity expansion compared with 5,582 MW or 71 percent of total capacity expansion when 80 percent of the budget is available.

The development of nuclear power will further be delayed by another important factor a longer gestation period which we shall discuss in the next section.

V. Test No. 4 ·· Impacts of Gestation Period

So far the analysis has been made under the assumption of immediate construction, i.e., zero gestation period. As long as certainty and no technical progress are assumed, the consideration of gestation periods of different types of plants has no significant impacts on the choice of techniques except the construction of plants should be started earlier than otherwise. However, the gestation period will play an important part for the choice of techniques where technical progress occurs. Where technical progress occurs steadily, the gestation period delays the realization of the benefits from technical progress. Table 13 shows the choice of techniques when gestation periods

<Table 12> **Optimum Capacity Expansion by Techniques under Technical Progress with Tight Budget Constraints** (Unit : MW)

Discount rate	Periods	Gas Turbine	Oil-fired thermal	Coal-fired thermal	Hydropower	Nuclear power	Total
9%	1967—1971	714	127	1,165	—	—	2,000
	1972—1976	1,017	684	—	—	1,081	2,782
	1977—1981	770	—	—	—	2,129	2,899
	Total	2,501	811	1,165	—	3,210	7,687
	%	32.5	10.6	15.1	—	41.8	100.0

Footnotes: (a) Only 60% of the budget is assumed to be actually available.
(b) Technical progress:
Conventional thermal power: 2% a year
Nuclear power : 5% a year

are considered. A two year gestation period is assumed for conventional thermal plants, three years for hydropower plants, and four years for nuclear power plants, The results are very interesting, At 5 and 7 percent discount rates, nuclear power becomes competitive to coalfired thermal plants in 1972, and it will be put into service in 1976. At 9 percent discount rate, the introduction is further delayed and nuclear power construction will begin in 1974 and will be in service in 1978.

Naturally, nuclear power amounts to only 20 to 35 percent of total capacity added during the planning horizon and most of this capacity will be in service only during the third planning period

Table 14 gives us some suggestive information as to the timing of the

<Table 13> Optimum Capacity Expansion by Techniques with Gestation Period

(Unit: MW)

Discount rate	Periods	Oil-fixed thermal	Coal-fired thermal	Hydropower I	Nuclear Power	Total
	1967—1971	885	792	515	—	2,192
	1972—1976	939	1,196	525	323	2,983
5%	1977—1981	740	—	—	2,159	2,899
	Total	2,564	1,988	1,040	2,482	8,074
	%	31.8	24.6	12.9	30.7	100.0
	1967—1971	841	1,165	—	—	2,006
	1972—1976	1,065	1,523	—	194	2,782
7%	1977—1981	376	—	—	2,523	2,899
	Total	2,282	2,686	—	2,717	7,687
	%	29.7	34.9	—	35.4	100.0
	1967—1971	841	1,165	—	—	2,006
	1972—1976	890	1,892	—	—	2,782
9%	1977—1981	928	371	—	1,600	2,899
	Total	2,659	3,428	—	1,600	7,687
	%	34.6	44.6	—	20.8	100.0

Footnotes: (a) Technical progress:
Conventional thermal power: 2%
Hydropower : 0%
Nuclear power : 5%

(b) Gestation period:
Conventional thermal power: 2 years
Hydropower : 3 years
Nuclear power : 4 years

<<Table 14> Timing of Nuclear Power Introduction

Discount rate	Gestation period of nuclear power	Construction begins	In service
5%	3 years	1970	1973
	4 years	1972	1976
	5 years	1972	1977
7%	3 years	1970	1973
	4 years	1972	1976
	5 years	1975	1981
9%	3 years	1971	1974
	4 years	1974	1978
	5 years	1978	Not in the planning horizon

Note: Gestation period for conventional thermal plants and hypro plants kept unchanged, i.e.,
Conventional thermal plant: 2 years
Hydropower plant : 3 years

introduction of nuclear power to the power system according to different gestation periods. It is quite likely that gestation period for nuclear power construction is longer than four years and, therefore, the timing of introducing a nuclear plant must be the last half of the second planning period.

The gestation period also has a significant influence on the choice of techniques under uncertainty. Since no sufficient reserve capacity is maintained in Korea, an unexpected increase of demand forces the decision-makers to choose the techniques which shorter gestation periods such as gas turbine and conventional thermal plants regardless of their costs.(23) However, this is a short-run departure from optimum choice of techniques, and, therefore, it could be ignored in the long-run analysis.

VI. Test No. 5 ·· Coal vs, Oil; Some Considerations on Foreign Exchance Rates and Prices of Fossil Fuels

The considerations of gestation period and tight budget constraints lead

(23) This is what has happened in Korea in 1967. An unexpected increase of demand has resulted in construction of 150MW of gas turbine.

us to conclude that, for the next 15 years, a large portion of power development will still be conventional thermal plants. Thus, it is very interesting to investigate competitive positions between the Korean anthracite coal-fired thermal plants and the imported oil-fired thermal plants under various prices of coal and oil. For simplicity, it is assumed that nuclear power plants will not be constructed during the next 15 years. The test has been repeated under various prices of Korean-anthracite coal and imported oil.

It turns out that, at the present price level, coal-fired thermal plants are favored in comparison to oil-fired thermal plants for base loads, whereas the latter dominates the former for peak loads. In converting the price of Korean-anthracite coal into U.S. dollars, the official foreign exchange rate is used. It is often argued, however, that the official foreign exchange rate does not reflect the true value of foreign exchange in underdeveloped countries. In Korea, the black market rate is approximately 10 percent higher than the official rate in terms of Korean currency. Hence, if this black market rate is used, the competitive position of coal-fired thermal will be strengthened. So a 10 percent decrease of the coal price in terms of U.S. dollars due to foreign exchange rate is considered. It appears that a 10 percent decrease of the coal price does not affect the choice of techniques i.e., oil-fired thermal plants are still competitive peak use. The test is repeated by assuming a 10 percent increase of oil price in addition to a 10 percent decrease of the coal price. The choice still remains unchanged.

Contrary to the favorable movement of prices for coal-fired thermal plants, it is also conceivable that the price of Korean-anthracite coal might go up due to increasing difficulty in coal-mining. It turns out that a 10 percent increase of the coal price would threaten the competitive position of coal-fired thermal plants for base loads.

It could be concluded that as long as the price of coal remains at the present level, coal, fired thermal plants are favored for base loads. However, because of the increasing demand for Korean-anthracite coal we may be faced with a coal shortage and steeply rising costs in the near future. This may limit the development of coal-fired thermal plants.

VII. Test No. 6 ·· Uncertainty

1. Uncertainty in water inflow

Since the level of the availability of a hydropower plant depends on the inflow of water, the dependable supply from a hydropower plant is uncertain unless it has a sufficiently big reservoir. In Korea, in general, reserve sites will permit only small reserves and there is little opportunity for storage that will adjust the run-off in the water sheds concerned over a year's time. In order to take into account the uncertainty in supply, the idea of chance-constrained programming is adopted. The dependable capacity of a hydropower plant reduced to the level at which 90 percent guarantee can be attained. In other words, both α and β for hydropower plants are taken to be 0.41 instead of 0.54. The consideration of uncertainty further discourages the development of hydropower. It turns out that hydropower is not competitive to coal-fired thermal plants for base loads even at a 5 percent discount rate. This strongly tempts us to conclude that, from a strictly economic viewpoint, no hydropower should be constructed for the purpose of power supply only. Naturally, the justification of construction of a hydropower plant has to be based on the benefits other than power generation such as irrigation, flood control and water pool for industrial use. Hence, it may be interesting to get some information as to how large the other benefits must be in order to justify the development of hydropower. For this purpose, it is assumed that the entire potential capacity of hydropower group I must be developed during the planning horizon. Tables 15 and 16 show rough estimates as to how large the average benefits

<Table 15> **Costs of Forced Development of Hydropower Group 1 under Certainty**

Discount rate	5%	7%	9%
Total discounted costs: No forced hydropower development (A)	$1,130,118,359	$1,046,223,234	$915,052,859
Total discounted costs: Forced hydropower development (B)	1,188,795,047	1,087,972,000	974,665,711
Increase of discounted costs due to forced development (B−A)	48,677,688	41,748,766	59,614,852
(B−A)/Hydro capacity developed	$46.80	$40.14	$57.32

<Table 16> **Costs of Forced Development of Hydropower Group 1 under Uncertainty**

Discount rate	5%	7%	9%
Total discounted costs: No forced hydropower development (A)	$1,140,118,359	$1,046,223,234	$915,052,859
Total discounted costs: Forced hydropower development (B)	1,226,031,562	1,119,359,094	1,003,975,156
Discounted cost increase due to forced development (B−A)	85,913,203	73,136,860	88,922,297
(B−A)/Hydro capacity developed	$82.60	$70.32	$85.50

other than power generation should be if the development of hydropower can be justified. Of course the numerical values in the tables should not be taken seriously, since they represent average figures obtained under strictly simplified assumptions. It is essential to evaluate any possible benefits other than power generation for each hydro site under consideration, It may be safe to say that the development of hydropower for power generation only is not competitive with conventional thermal plants at reasonable discount rates and uncertainty in water inflow further reduces the economic value of hydropower. As a result, only a considerable amount of benefits other than power generation can justify the development of hydrpower in Korea.

2. Uncertainty in Demand

The significance of uncertainty in supply will be greatly reduced in the future, since the potential capacity of hydropower is far less than the required capacity expansion. Even though we will develop all the hydro sites whose capacity is 20 MW or more, hydropower will be less than 15 percent of total system capacity in 1981.

Hence, the real problem is not uncertainty in supply, but uncertainty in demand, In demand projection, some variance of actual from estimated figures is inevitable. Then the matter is how a decision-maker takes into account this uncertainty in his decision-making so as to minimize harmful impacts from such variance. Decision theory under uncertainty would easily provide a rational solution if the probability distribution of demand, the cost of additional capacity and penalty cost of not meeting demand can be estimated. In fact, however, it is almost impossible to derive a probability distribution of demand for electric power from data available now in Korea. At best, two or more different projections can be made under different assumtions as to development and structural change of the economy. The demand projection done by the Korea Electric Company in 1967 represents a somewhat optimistic view.(24) It is generally thought that it is better to use optimistic projection as the base of capacity expansion partly because the penalty cost of not meeting demand for electric power is relatively high and partly because demand for electric power has been and will be growing.

However, there are two reasons which tend to favor using less optimistic projection. First, the penalty cost of not meeting peak demand in Korea will be far less than that of industrialized societies. Secondly, because of the lack of capital, if the capacity expansion is based on optimistic projection, we may be forced to choose an expensive alternative. Table 17 shows possible cost saving at various levels of availability of capital when capacity expansion is 10 percent less than the optimistic projection. It is apparent that the tighter the budget constraints, the greater the cost saving from not meeting some of peak demand. Of course, the cost saving has to be

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(24) It is assumed that G.N.P. will grow 10 and 7 percent per annum during the period of 1967~1971, and 1972~1976, respectively. The growth rate of 10 percent per annum is still optimistic even if we encounter a favorable movement in Korean economy during the last few years. The average growth rate of G.N.P. during the first economic development plan was 8.3 percent per annum and the growth rate is estimated to be approximately 8 percent in 1967.

compared with the expected value of the penalty costs. If the penalty cost is not much higher than the cost of providing additionnal capacity and the budget is very tight, it may be better to accept the *conservative* projection for capacity expansion.(25)

<Table 17> Cost Saving from Not Meeting 10% of the Peak Demand (in thousand U.S. dollars)

Availability of budget	Total discounted costs of meeting optimistic projection	Total discounted costs of meeting 10% less than optimistic projection	Difference
100%	1,182,322	1,104,684	77,638
80%	1,185,087	1,107,152	77,935
70%	1,188,351	1,108,708	79,643
60%	1,214,411	1,113,994	1004,17

Footnote: 7 percent discount rate is used.

VIII. General Implications of the Tests

In order to investigate the significance of impacts of some important factors on the choice of techniques in the electric power industry in Korea, the tests have been repeated under a number of different assumptions as to these factors. Following is a summary of general implications of the tests.

(1) The choice of techniques is sensitive to the discount rate, Taking around 7 percent as appropriate discount rate, the development of hydropower group I and conventional thermal plants(coal-fired thermal plants for base loads and oil-fired thermal plants for peak loads)turn out to be optimum choice *at present prices of fuels,*

(2) However, the development of hydropower is greatly discouraged mainly because of the lack of capital for the power development in Korea. The proportion of hydropower to total capacity expansion during the planning horizon should remain relatively small, less than 9 percent, if the

(25) This problem can be formalized in terms of game theory, although it may be very difficult to get a payoff matrix in practice.

decision-makers want to satisfy a rapidly growing demand. As a consequence, a large proportion of capacity expansion during this horizon should consist of conventional thermal plants, and the optimum choices under budget constraints look very much similar regardless of the discount rates used. Furthermore, the construction of a considerable capacity of gas turbine may be required to meet the growing demand if the shortage of capital for power development becomes critical.

(3) There has been rapid technical progress in nuclear power in the last decade and this technical progress is more or less likely to continue in this field. The consideration of such technical progress in nuclear power suggests to us that the question of having nuclear plants in Korea which has only limited resources of conventional fuels is not one of principle but one of suitable timing, Although nuclear power plants have shown a decisive market break-though in advanced countries in the last few years, there are two reasons among others which delay the timing of installing nuclear plants in Korea. One is the lack of capital and the other is a long gestation period required for the construction of nuclear power plants. Our tests suggest, with several qualifications, the timing of the introduction of the first nuclear power plant should be the last half of the second planning period(i.e., around 1975). Earlier construction of nuclear power plants is not economically justified. Of course, since the construction of a nuclear power plant requires a relatively long period, it would be necessary to have a clear idea of the steps to be taken towards the actual construction of a nuclear power plant, The timing must be based on a careful analysis of existing domestic energy resources as well as technical progress in nuclear power.

(4) At present prices of Korean-anthracite coal and imported oil, coal-fired thermal plants are favored to oil-fired thermal plants for base loads, while the latter is favored to the former for peak loads.

The comparison between coal-fired thermal plants and oil-fired thermal plants involves problems of foreign exchange and the available amount of anthracite coal as well as the prices of coal and oil in the future. The consideration of foreign exchange strengthens the competitive position of coal-fired thermal plants, although they are still not economical for peak use. On the other hand, it may be expected that the costs of producing Korean anthractite coal will steadily increase due to the growing difficulty in coal mining. A 10 percent increase in the price of coal would endanger the competitive position of coal-fired thermal plants for base loads. Hence, the long-run planning of coal production and the estimation of future production cost must be the prerequisites of the choice of techniques in the electric power industry in Korea.

(5) Assuming that present capital and fuel costs will remain constant throughout the planning horizon, the development of hydropower group I is economically justified at a 7 percent discount rate, although only a part of the potential can actually be developed because of the budget constraints. However, the considerations of dis-economies of scale and uncertainty in dependable capacity greatly weaken the competitive position of hydropower. It turns out that hydropower plant is not competitive with conventional thermal plants for power generation at an appropriate discount rate, although the generalization has only a limited meaning since hydropower belongs to the realm of prototype selection rather than group selection. Hence, in most cases, the justification of the construction of hydropower plants has to be based on the considerations of the benefits other than power generation, such as irrigation, flood control. A careful evaluation of all the benefits from each hydro site is essential.

V. SECONDARY AND INTANGIBLE FACTORS

In the previous chapter, general implications of the test results have been presented, In reaching these generalizations, it has been necessary to make a number of simplifying assumptions and to ignore extra-economic factors. These assumptions and the elimination of extra-economic consequences tend to bias the conclusions in certain ways. Thus it would be worthwhile to describe the more important of these assumptions and extra-economic consequences and supplement the conclusions we have obtained from the simplified models.

I. Prospect of Nuclear Power Development

We have concluded that the question of having nuclear plants in Korea is not one of principle but one of suitable timing. We have pointed out that, in spite of a rapid progress in nuclear technology, the dominance of nuclear power in Korea will be delayed mainly because of the lack of capital and a long gestation period required for the construction. These are the conclusions obtained under a number of simplifying assumptions. However, nuclear power is a complex technological field in which the scale of development will largely be determined by the expertise built up in all its aspects. In an analysis of prospects for nuclear power today, therefore, what is required is not merely to attempt to investigate the economic feasibility of nuclear power, but rather to conduct a searching examination of the technological, social and political factors as well as economic factors which are likely to determine the timing of the introduction of nuclear power. Virtually all aspects of the industrial and political situations of countries are involved in making this decision. In this section, therefore, we will examine some important factors...favorable and unfavorable...ignored in the model. Let us, first, consider factors favoring development of nuclear power.

1. Impacts on technical skills

The construction of a nuclear power plant requires special skills in such fields as the installation of reactor components, construction of containment vessels, reactor shielding, welding, instrumentation and controls, etc. The operation of a nuclear power plant requires a highly trained technical staff of nuclear engineers, reactor operators, electronic engineers and skilled technicians. Hence, an earlier introduction of nuclear power plants may facilitate the development of such technical skills. This development will generally contribute to scientific and technical progress in Korea. Of course, as a developing country, Korea will not be able to promote the development and utilization of nuclear power independently in the foreseeable future. Nevertheless, the importance of impacts from the construction of nuclear power plants on the technical progress in the future may not simply be ignored,

2. Diversification of energy resources

Most of the energy requirement in Korea has been met by the domestic resources so far. However, since the domestic resources are very limited, it is natural to expect that the increasing demand for energy has to be met by imported oil. Import of oil has been rapidly increased in the last few years and such a tendency is likely to continue so that the Korean economy will depend heavily on imported oil as, for example, the Japanese economy does today. However, considerations of security of energy supplies suggest that the heavy dependence of energy requirement on imported oil may not be desirable. The introduction of nuclear power by reducing the oil requirements would serve the diversification of energy sources and may contribute toward bringing better bargaining position in purchasing oil in the future.

3. Political motivation

It is conceivable that political leaders might feel that an earlier introduction of nuclear power may raise the prestige of the country. This sort of political desire favors development of nuclear power regardless of economic efficiency.

Some other factors seem to be unfavorable to nuclear power.

4. Safety consideraions

It has been indicated that the safety and control provisions incorporated in various types of commercial nuclear plants have performed satisfactorily and reliably. However, it is conceivable that safety considerations may give rise to additional costs. For example, if a nuclear plant is located away from the ocean, it would probably be necessary to use substantial quantities of fresh water consumptively for cooling purposes. The use of river water may lead to an unacceptable rise in water temperatures or unacceptable radiation hazard. Since Korea is a peninsula country, it would not be difficult to find sites near the ocean. But this consideration may increase transmission costs by restricting possible sites of nuclear power.

The considerations of safety make the adoption of nuclear power legislation one of the important prerequisites for undertaking a nuclear power plant. Such legislation is necessary to establish regulatory control over nuclear power facilities and materials with a view to protecting public health.

5. Unexpected failure and plant capacity factor

Since nuclear power is capital intensive, the plant capacity factor is very important. In the early stage of nuclear introduction, it is conceivable that the plant capacity factor may be low because of the lack of technical skills and experience. The dependability of nuclear power has to be evaluated carefully in the future. So far, none of the large pressurized water or boiling water reactors have begun routine operation. In the United States, the plant at San Onofre, a 430 MW pressurized reactor, has experienced some start-up trouble with its turbines; and in Oyster Creek, the boiling water reactor that set off the wave of buying is not scheduled for operation until 1968. Unexpected failure may be more frequent and the costs of required readjustment may be higher in underdeveloped countries than in developed countries. Also, the economic consequences of an unexpected failure will be more severe in the case of nuclear power because plants will typically be bigger than conventional plants.

6. Prices of conventional auels

Any future comparison of nuclear and conventional power involves certain assumptions about the future prices of fossil fuels. In our analysis, these prices were assumed to be constant. There is little chance that the production cost of Korean-anthracite coal may decrease. However, it is often suggested that oil price may be lowered to permit oil-fired plants to continually undercut nuclear plants. To assess how far this is possible would be difficult. But it is certainly conceivable that the oil supplier would try to reduce his supply price in the case of the widespread availability of cheap nuclear power.(1)

7. Nuclear fuels

The fuel supply arrangements for nuclear power pose certain special problems not encountered with fossil-fuel plants. While fuel-oil supplies can be negotiated directly from private suppliers, there is greater governmental involvement in the procurement and use of nuclear fuels. Their sale by one country to another is usually carried out under bilateral or international agreements. While the price of natural uranium is determined largely by producers according to the laws of supply and demand, the price of enriched uranium is at present fixed by government agencies in the producing countries. Although this price approximates the actual cost of production, one cannot rule out the influence of other factors, Suitable short-or long-term contracts for the supply of nuclear fuel should be arranged before a considerable expansion in nuclear power. In the analysis, the costs of

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(1) One good example in the United States is that in situations where utilities are known to be seriously considering a nuclear projects substantial cuts were made in coal prices, mainly through the granting of favorable unit train rates for coal delivery. See J.H. Horgerton, *op. cit.*, p. 27.

nuclear fuel are assumed to decrease due to the progress in nuclear technology.[2] However, the price of uranium may go up as demand increases in the future and offset any reduction in fuel requirements attained by technical progress.

II. The Coal-Fired Thermal Power and Coal Industry

It has been concluded that the Korean-anthracite coal-fired thermal plants are favored over the imported oil-fired thermal plants for base loads. It has also been pointed out that approximately a 10 percent increase of production costs of anthracite coal or a 10 percent decrease of the oil price would make oil-fired thermal plants competitive with coal-fired thermal plants for base loads. In fact, increasing production costs have been reported as demand for coal has grown in the last few years. Since the electric power industry is a major user of Korean anthracite coal, the impacts on the coal industry of the choice in the electric power industry have to be carefully evaluated. The following factors deserve to be mentioned.

1. Employment effect

The coal industry has the important advantage that it provides the maximum direct employment among all energy sectors. Since we have taken the sectorial approach, the employment effects have been ignored in our analysis. In labor surplus economies such as the Korean economy, the employment effects should be given a credit on the basis of social policy as well as economic policy. Special attention should therefore be given to the coal industry, with a view to ensuring the stable consumption of this commodity as far as possible.

2. Coal is a domestic natural resource

Anthracite coal is the only locally available source of fuel in Korea. This

(2) For example, it is expected that the successful development of breeder reactors would considerably reduce nuclear fuel costs per KWH in the future.

fact gives rise to two specific advantages of coal-fired thermal plants. One is the saving of foreign exchange and the other is the security of supply. The saving of foreign exchange has been considered in our models by using a premium-added foreign exchange rate. Under critical shortage of foreign exchange, it is perhaps advisable to give priority to coal-fired thermal plants regardless of the cost aspect. (Or as economists would prefer to phrase it, a heavy penalty is put on the use of foreign exchange.) As the position of foreign exchange improves, the idea of a free choice of energy sources may replace the coal-preference policy, and emphasis should be placed on achieving power supply at the cheapest rates. Cheapness of power will be of special importance to the Korean economy when it enters into the group of open economies since it is essential for promoting the international competitiveness of its industries.

Domestic resources also contribute to the *security* of the power supply. This advantage is certainly difficult to calculate but it cannot be ignored.

We may conclude that the impacts on the coal industry of the choice of techniques in the electric power industry require careful analysis, both from the point of view of the demand for coal and of the capacity of the industry to supply coal at competitive prices.

III. Development of Hydropower

In the previous chapter, we concluded that hydropower developed for the purpose of power generation only does not compete with conventional thermal plants or nuclear power plants at reasonable discount rates, It has also been emphasized that this generalization has only a limited value because of the variability of each hydro site. The evaluation of each hydro site must be carried out including the benefits from flood control, irrigation, and the supply of industrial water. In some cases, the above benefits turn out to be substiantal. The A.I.D. survey team evaluated the economic feasibility of five potential sites. The benefits from flood control, irrigation and the supply of industrial water were explicitly considered for the evaluation of one hydro site. For this site, the benefits other than power generation were estimated to be 35 percent of the value of power generation.(3)

In addition to these benefits, other considerations should also be included in the evaluation of hydropower.

1. Flexibility of supply

A hydropower plant is, in general, able to respond much more quickly to the system frequency. This quicker response time is useful for governing the system frequency. Such flexibility of supply may not be of much value during normal operation.

2. Water power as a domestic natural resource

As indicated in the previous section, such a resource has special advantages from the standpoint of security of national supply although they are difficult to calculate.

3. Interdependence of hydro sites along the same river

In the model, it is assumed that each hydro site is independent of other hydro sites. obviously, this is not true for the sites along the same river. For example, storage of water at upstream power plants would increase the power output of all plants downstream. This is the reason why the basin approach is necessary.

4. Employment effects during construction

The construction of a hydro plant provides a great employment effect during the period of construction. Since a considerable amount of disguised unemployment exists in the rural areas in Korea, the construction of

(3) The survey concluded that the site is not economically justified even with the considerations on the benefits. However, it turns out that this conclusion is mainly due to the inclusion of tax, proportionate to capital costs, which is not relevant for the choice of the investments on the basis of national interest. Elimination of such a tax would justify the project. See the Survey Team, *op. cit.*, Vol. I, pp. 118—123.

hydropower plants may effectively utilize the disguised unemployment. Such utilization is desirable from the viewpoint of social policy, as well as economic policy.

5. No danger of air pollution or radioactive materials

Furthermore, it generally contributes to the beauty of the country(4) and provides pleasant recreation places.

6. Transmission costs

In our models, transmission costs were not considered. Since hydro sites may be far from the market where the electric power is needed, such sites would increase the transmission costs. The difference in transmission costs between a hydro plant and alternative thermal plant seems to be not significant in Korea since hydro sites are relatively well distributed in the country. Nevertheless, the consideration of this difference should be made whenever hydro sites are examined for development.

7. Relocation of farmers

The construction of hydropower plants may require the relocation of farmers.

IV. Consideration of the above factors certainly suggest that the use of The mathematical programming techniques will never seriously reduce the importance of the detailed evaluation of each project. Enough has been said to indicate that too great a degree of reliance should not be placed upon the numerical results. The simplifications and assumptions required in the models are too extreme to allow us to expect anything like a precise investment plan for the next 15 years. All we can hope for, at least at this moment, is a fairly generalized picture of the main lines of development which a long-run development plan ought to follow. But this is a great

(4) Of course, this is not always the case. The construction of hydropower plant may impair the natural scenic beauty.

deal better than nothing.

VI. CONCLUSIONS

This study was an attempt to apply mathematical programming to investment problems in the electric power industry in Korea. In the process of this study, I have constantly been aware of the limitations of applying mathematical programming to the relatively complex investment problems at industry level in developing countries such as Korea.

It may be worthwhile here to recall the controversy, a decade ago, as to the feasible and desirable role of operations research in developing countries. Ackoff expressed his confidence on operations research by saying that:

> I feel strongly that we should try to apply OR in planning the development of underdeveloped nations. It seems to me that there is hardly anything OR as a profession could do which contributes more to the possibility of international peace and prosperity.(1)

Hitch strongly disagreed with Ackoff and urged caution in extending operations research to national problems, particularly in developing countries. He said;

> ...[that] operations research is the art of suboptimizing, i.e., of solving some lower-level problems, and that difficulties increase and our special competence diminishes by an order of magnitude with every level of decision making we attempt to ascend.(2)

Then he concluded:

(1) R.A. Ackoff, "Operations Research and National Planning," *Operations Research*, Aug. 1957, p. 458.

(2) C.U. Hitch, "Operations Research and National Planning A Dissent," *Operations Research*, Oct. 1957, p. 718.

I hope that we can help the underdeveloped countries and think that our chances of doing so will be enhanced if we start by attacking management problems in an enquiring and experimental spirit.[3]

In general, it seems to me that a cautionary view has much to recommend it for industry-level problems as well as nationwide planning problems. It has been well recognized that a clear and reducible objective function, a well-structured model, and abundant and reliable data are essential prerequisites of any successful application of operations research techniques. We have seen in our studies all the aspects of investment problems over time and space in the electric power industry could not adequately be reflected by simple models. Furthermore, reliable data is in short supply and uncertainty is significant in developing countries. Nevertheless, this study has demonstrated that an attempt to apply operations research techniques such as mathematical programming to the investment problems in key industries provides us some insight into the characteristics of those problems in developing countries. The usefulness of such an attempt has been shown in the following aspects:

(1) It was necessary, for the formulation of the models, to make efforts to learn what the objectives of these investment problems really are and to identify the complex interrelations between variables. Obviously, some of the objectives (e.g., the security of power supply) were difficult, if not impossible, to measure quantitatively, and the interrelations between variables were too complex to be reflected by simple models. Nevertheless, an attempt itself to clarify the objectives and interrelations contributes a great deal to the understanding of those problems by yielding a clear and sometimes new insight into the problem.

(2) Sensitivity analysis has mainly been used in handling the uncertainty surrounding such factors as discount rate, available capital, technical progress,

(3) *Ibid.*, p.723.

factor prices, demand, etc. Sensitivity analysis was found to be a relatively simple method of handling uncertainty. Its application to the investment problems highlighted the importance of the discount rate, the amount of capital available for power development, technical progress, and possible errors in cost estimation. Sensitivity analysis obviously requires a great deal of computational efforts and, moreover, there is no guarantee that any given sensitivity analysis has included all the relevant alternatives. Advances in computer technology would overcome these limitations to some extent. It seems to me, however, that the most critical weakness of sensitivity analysis rests on the fact that it provides a large volume of difficult-to-display numbers to the decision makers who really want one figure. It does not provide the "best" solution but provides an array of solutions optimal under various conditions imposed by the analyst. The choice among the members of this array still remains in the hands of decision makers, although their decisions can be greatly helped by the organized information obtained by sensitivity analysis.

(3) It has been shown how any scarce resource can be explicitly incorporated into the models and how its value in the industry can be estimated by making use of the concept of shadow prices. Where market prices do not correctly reflect the real values of resources, the concept of shadow prices can be used for improving allocation of these resources. For example, the shadow price of capital for power development in each planning period were obtained in the study. This information would certainly be useful in re-evaluating the budget allocation between planning periods in the electric power industry and between key industries which compete for the capital with the electric power industry. It is apparent that any scarce resources other than capital can be incorporated into the model by adding appropriate constraints to the primal problem and the shadow prices of these resources will be obtained as dual solutions.

(4) It has been pointed out that the application of mathematical prog-

ramming would never seriously reduce the importance of the detailed evaluation of each project. However, individual project evaluation would not visualize the broad lines of a long-run power development because it is too complex to deal with the immense number of constraints and unknowns which would be involved in a long-run analysis. On the other hand, the application of mathematical programming at industry level provides a fairly generalized picture of the broad lines of development which a long-run development plan ought to follow. Such a generalized picture as to the nature and directions of power development can certainly be useful for designing a long-run power development plan.

This type of analysis is necessarily incomplete. The analysis can never treat all the considerations that may be relevant even with no limitations of time and money. But, at the very least, the method used offers a way to choose the numerical quantities related to a long-run power development so that they are logically consistent with each other, with an assumed objective, and with the calculator's expectation of the future. The method provides its answers by processes that are accessible to critical examination, capable of duplication by others, and, more or less, *readily modified as new information becomes available.*

Bibliography

Books

Charnes, A., and Cooper, W.W. *Management Models and Industrial Application of Linear Programming*, Vols. I and II. John Wiley & Sons, Inc., 1960.

Chenery, H.B., and Clark, P.G. *Interindustry Economics.* John Wiley & Sons, Inc., 1964.

Dantzig, G.B. *Linear Programming and Extensions.* Princeton, N.J.: Princeton University Press, 1963.

Dorfman, R., Samuelson, P.A., and Solow, R. *Linear Programming and*

Economic Analysis. New York: McGraw-Hill Book Co., 1959.

Hadley, G. *Linear Programming*. Addison-Wesley Publishing Co., 1962.

Hadley, G. *Nonlinear and Dynamic Programming*. Addison-Wesley Publishing Co., 1964.

Henderson, J.M. *The Efficiency of the Coal Industry*. Cambridge, Mass.: Harvard University Press, 1958.

Hirschleifer, J., DeHaven, J.C., and Millman, J.W. *Water Supply*. Chicago, Ill.: University of Chicago Press, 1960.

Kendrick, D.A. *Programming Investment in the Process Industries: An Approach to Sectoral Planning*. Cambridge, Mass.: The M.I.T. Press, 1967.

Krutilla, J.V., and Eckstein, O. *Multiple Purpose River Development*. The Johns Hopkins Press, 1958.

Manne, A.S. (ed.). *Investments for Capacity Expansion: Size, Location, and Time-Phasing*. Cambridge, Mass.: The M.I.T. Press, 1967.

Manne, A.S., and Markowitz, H.M.(eds.). *Studies in Process Analysis*. New York, 1963.

Marglin, S.A. *Approaches to Dynamic Investment Planning*. Amsterdam, North Holland Publishing Co., 1967.

Masse, P. *Optimal Investment Decisions: Rules for Action and Criteria for Choice*. Prentice Hall, 1962.

Nelson, J. R.(ed.). *Marginal Cost Pricing in Practice*. Prentice Hall, 1964.

Qayum, A. *Theory and Policy of Accounting Prices*. Amsterdam: North Holland Publishing Co., 1959.

Sen, A.K *Choice of Technique: An Aspect of the Theory of Planned Economic Development*, Oxford, 1960.

Articles

Ackoff, R.A., "Operations Research and National Planning," *Operations Research*, August 1957.

Arrow, K.J., "Decision Theory and Operations Research," *Operations Research.*, December 1957.

Barzel, Y., "Productivity in the Electric Power Industry, 1929—1955," *The Review of Economics and Statistics*, November 1963.

———, "The Production Function and Technical Change in the Steam-Power Industry," *The Journal of Political Economy*, April 1964.

Bates, R.W., "Capital Costs and the Peak Problem in Electricity Supply," *The Mancester School of Economic and Social Studies*, May 1963.

Boiteux, M., "Peak Load Pricing," *Journal of Business*, April 1960.

Charnes, A., and Cooper, W.W., "Chance Constrained Programming," *Management Science*, October 1959.

———, "Deterministic Equivalents for Optimizing and Satisficing under Chance Constraints," *Operations Research*, January-February 1963.

Chenery, H.B., "Overcapacity and the Acceleration Principle," *Econometrica*, January 1952.

Chenery, H., and Kretschmer, K., "Resource Allocation for Economic Development," *Econometrica*, October 1956.

Fetter, R. B., "A Linear Programming Model for Long Range Capacity Planning," *Management Science*, July 1961.

Henderson, J.M., "A Short-Run Model for the Coal Industry," *The Review of Economics and Statistics*, November 1955.

Hitch, C. J., "Operations Research and National Planning A Dissent," *Operations Research*, October 1957.

Horgerton, J.H., "The Arrival of Nuclear Power," *Scientific American*, February 1968.

Houthakker, H.S., "Electricity Tarrifs in Theory and Practice," *Economic Journal*, March 1951.

Johnston, J., "Statistical Cost Functions in Electricity Supply," *Oxford Economic Papers*, February 1952.

Komiya, R., "Technlogical Progress and the Production Function in the

United States Steam Power Industry," *The Review of Economics and Statistics*, May 1962.

Manne, A.S., "Capacity Expansion and Probabilistic Growth," *Econometrica*, October 1961.

Marschak, T., "Capital Budgeting and Pricing in the French Nationalized Industries," *Journal of Business*, April 1960.

Marse, P., and Gibrat, R., "Application of Linear Programming to Investments in the Electric Power Industry," *Management Science*, January 1957.

Meek, R.L., "The Allocation of Expenditure in the Electric Supply Industry: Some Methodological Problems," *Scottish Journal of Political Economy*, February 1963.

———, "An Application of Marginal Cost Pricing: The 'Green Tariff' in Theory and Practice," *Journal of Industrial Economics*, November 1963.

Prest, A. R., and Turvey, R., "Cost-Benefit Analysis: A Survey," *Economic Journal*, December 1965.

Turvey, R., "On Investment Choices in Electricity," *Oxford Economic Papers*, November 1963.

Ullmann, J. E., "Economics of Nuclear Power," *Advances in Nuclear Science and Technology*, edited by E.J. Henley, and H. Kouts, 1962.

Webb, M.G., "Some Principles Involved in the Economic Comparison of Power Station," *The Manchester School of Economic and Social Studies*, January 1967.

Public Documents

The Council for Planning and Coordination. *The Evaluation of the First Five-Year Economic Development Plan* (1962—1966). Seoul, Korea, 1967 (in Korean).

Crean, L. E., Laubarstein, R. A., and Mins, L.S. *Comments on Some Aspects of Nuclear Power Economics.* International Atomic Energy Agency, Review

Series No. 9, Vienna, Austria, 1961.

Gilinsky, V., and Lange, P. *The Japanese Civilian Nuclear Program,* The Rand Corporation, Memorandum RM-5366-PR, August 1967.

International Atomic Energy Agency, "Nuclear Power Costs," *International Atomic Energy Agency Bulletin,* October 1963.

———, "Nuclear Power in Developing Areas," *International Atomic Energy Agency Bulletin,* April 1963.

———, *Proceedings of the Conference on Small and Medium Reactors.* Vienna, 1961.

Korea Electric Company. *An Outline of Ten-Year Power Development Plan* (1967—1976). Seoul, Korea, September 1967.

———, *Statistical Yearbook.* Seoul, Korea, 1965, 1966 and 1967 issues (in Korean).

Korea Electric Power Indutry Survey Team. *Korea Electric Power Survey,* Vols. I and II. Seoul, Korea, 1965.

Taiwan Power Company. *A Report on the Prospect of Nuclear Power in Taiwan.* Taipei, Taiwan, September 1964.

United Nations(E.C.A.F.E.) *The Role and Application of Electric Power in the Industrialization of Asia and the Far East.* Bangkok, Thailand, 1966.

———, "Economic Development and Planning in Asia and Far East, IX planning for Energy Development," *Economic Bulletin,* December 1965.

———, *Electric Power in Asia and Far East,* 1951—1955, 1956—1960, 1961—1962, 1963, 1964. Bangkok, Thailand.

———, *Proceedings of the Regional Seminar on Energy Resources and Electric Power Development.* Bangkok, Thailand, 1962.

United Nations(E.C.E). *Economic Methods and Criteria Used in the Selection of Investments in the Electric Power Industry.* Geneva,1963.

United Nations Development Programme and International Atomic Energy Agency. *Pre-investment Study on Power Including Nuclear Power in Luzon, Republic of the Philippines.* Vienna, Austria, 1966.