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WASP AND ELECTRICITY CAPACITY EXPANSION PLANNING FOR EMERGING COUNTRIES

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1. INTRODUCTION

The WIEN Automatic System Planning Package (WASP) is typical of electrical generation capacity expansion planning models in general use today. It was developed by the Tennessee Valley Authority (TVA) for the International Atomic Energy Agency (IAEA) hence the name WIEN. It is available without charge to member states. Assistance in its use is available from IAEA staff and in addition it is well documented. User conferences are held at infrequent intervals. The next one is scheduled for March 1981 at Ohio State University in Columbus, Ohio.

The user of WASP should be aware of its uses and limitations especially, though not exclusively, in its application to emerging countries. The objectives of this paper are as follows:

A. To present an overview of capacity expansion planning and its place in the economic planning process with reference to the emerging countries.

B. To describe in a general way the use of WASP.

C. To caution case in the interpretation of WASP results.

D. To suggest the way in which WASP can be used to assess innovative electric generating technologies.

Complicating the electric system planning process is the ideological and symbolic significance with which electrification has been endowed. We need only recall Lenin's assertion that Communism is Soviet power and the electrification of the whole country; the mystique of vast undertakings such as TVA, Dnieperpetrovsk Hydro Project, and the Aswan High Dam; the art which glorified electrification which emerged in the 1930's in the United States, the Soviet Union and Fascist countries as well. As a symbol of progress, electrification became an end in itself and remains so in many emerging countries.

To my mind, the pace of development of electric energy supply is rationally governed by anticipations of future demands on the one hand while on the other it is constrained principally by limitations on available capital resources. The probability of demands of specified magnitude occuring at various places in the country is a function of economic development which is driven by the planning process. Electric system planners must be informed of the consequences for electricity supply requirements of the economic development plan. Economic development planners for their part must ensure that electricity supply is available where, at the time, and in such quantity as is required. In doing so they must provide necessary financial and physical resources for investment and operations. Thus a two-way flow of information must be established between economic development planners and electricity supply planners. A schematic representation of this information exchange is shown in Figure 1.

The position which I have enunciated above is in direct opposition to one which maintains that the availability of electricity supply calls forth economic development. Providing electricity to the unelectrified

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Figure 1.

countryside is not an effort to be undertaken lightly and investments in electricity supply should not be made unless an adequate return is assured. Investment in electricity supply is only justifiable in the context of alternative investment opportunities.

Another argument frequently heard for electrification is founded on a concept of social justice which asserts that the amenities which can be made available only by electrification should be provided to the inhabitants of rural areas as well as those in urban areas. It is further argued that the availability of such amenities help stem an undesirable rural-urban migration. One weakness in these arguments relates to the fact that providing electric service is of itself insufficient to assure the enjoyment of such amenities where the populace is unable to provide consumer durable. Another is that it is extremely doubtful that the availability of the amenities of electric supply ever actually affects rural-urban migration. It is much more likely that such migration is driven by under-employment in the countryside and is likely to be slowed by the creation of productive enterprises in rural areas. This, of course, takes us back to the primacy of a development plan. It should also be remarked that planners may make a conscious decision to provide electric service even when no economic return to such an investment is forthcoming. Such a decision should be made in context of the allocation of national income between investment and consumption and expenditure on electric supply is then included with consumption expenditure.

2. ELECTRIC SYSTEM PLANNING

Capacity expansion models are appropriate when a grid exists or is planned. In the early stages of development an electric grid may be premature and dispersed supply may be preferable. This may be the case when economies of scale in investment in electricity supply are not available and when reliability of supply is not highly valued. This will generally be true when electric loads are small and scattered in which case electric service may be provided by diesel engine generating sets, low head hydro-electric installations and supply based on appropriate renewable resources.

In considering the development of a new electric grid or the extension of an existing grid the planner must also consider alternative energy options. To what extent is electricity the optimal energy supply for planned industrial or agricultural enteprise? Consider the following list of functions for which electricity may substitute for other energy forms.

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AGRICULTURAL SECTOR

1. Irrigation Pumping
2. Threshing
3. Refrigeration
4. Crop Drying
5. Farm Residences

INDUSTRIAL SECTOR

1. Process Heat

TRANSPORT

1. Urban and Interurban Mass Transit

In the residential sector as was suggested above, planners must determine whether or not householders have sufficient income to purchase consumer durables needed to obtain the benefits from electric supply.

The decision having been made that an electric grid is appropriate the capacity model develop an expansion plan, given the present state of the generating system, which will be capable of supplying a set of given energy demands with a specified minimum reliability at least cost. The basic information required includes the characteristics of existing generating units, the loads to be imposed on the system during the study period and alternative allowable expansion plans.

WASP employs six subprograms in the determination of an optimal expansion plan. They include the following:

a. Fixed system programs
b. Load description program
c. Variable system program
d. Expansion configuration program
e. Merge and simulate program.

Descriptions of these programs from WASP documentation are in the paragraphs which follow.

Fixed System Program

The Fixed System Program describes the state of the existing power system at the start of the study. The required data for each generating station in the system include: number of identical units, minimum and maximum operating capacities, heat rates associated with these capacities, type of fuel, fuel cost, forced-outage rate, and maintenance requirements. Any firmly committed additions and/or unit retirements are also specified in this program. Committed additions are described in the same manner as for existing plants with the exception that the first year of operation must also be specified. The date of retirement must be specified for unit retirements.

Variable System Program

The Variable System Program defines the type of units that will be used to expand the system during the study period. Each particular unit whose type and capacity are defined becomes an expansion candidate. For

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example, a 600-MW nuclear unit and a 1000-MW nuclear unit would consti-
tute different expansion candidates. Hydroelectric and/or pumped storage
projects can also be included as expansion candidates. The data required
to define a particular candidate are identical to those used in the fixed
system program.

Load Description Program

The Load Description Program defines the generation requirements in
each period of the study. The study is nominally divided into years;
however, each year may be subdivided into a number of periods. The fore-
casted peak loads and shape of the load duration curve are defined for
each period in this program.

Expansion Configuration Generator Program (CONGEN)

The Expansion Configuration Generator Program gives the system
planner the ability to direct the area of study to expansion configura-
tions that he believes to be most economic. This can be accomplished by
specifying minimum and maximum reserve requirements, thus constraining
the system capacity. Any expansion configuration whose capacity would
fall outside the reserve requirements would not be considered as a feas-
ible state. Limits can also be placed on the minimum and maximum number
of units of a particular expansion candidate that can be installed in any
given year. The CONGEN program forms a list of all allowable system con-
figurations (or states) for each year in the study.

Optimization Program (DYNPRO)

The DYNPRO program uses a dynamic programming algorithm to determine
the optimal system expansion policy from the states defined in the CONGEN
program. All the economic calculations, including the escalation of fuel
prices, penalty on foreign expenditures, and present-worth calculations,
are performed in the program.

The critical loss-of-load probability can be defined for any year of
the study. Any configuration having a poorer reliability than the criti-
cal value is not considered as a feasible state and is omitted from the
optimization calculations. After the optimum expansion schedule has been
calculated, the DYNPRO program will tell the user if any of the restric-
tions used in the CONGEN program acted as a constraint on the solution.

Merge and Simulate Program (MERSIM)

This program calculates the operating cost for each of the configu-
rations generated by the CONGEN program. A Probabilistic Simulation
Model is used to calculate the unit loadings and the system operating
cost. The reliability of the generating system will not be able to meet
the system load and the probable amount of unserved energy. In addition
to calculating the total operating cost, the MERSIM program calculates
the cumulative expenditure with separate accounting in local and foreign
currency.

An examination of these subprograms reveal areas where the judgement
(or intentions) of the planner influence the outcomes. They are as fol-
lows:

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Variable System Program

Here the analyst selects expansion candidates which the program considers. Furthermore, he must specify the year in which they are to become operational. For instance, he may permit the model to consider 600MW nuclear units, a 200MW coal unit, and no others to meet the capacity exapnsion needs in 1990. In addition, he must specify economic and technical data of each candidate, capital cost, operating and maintenance costs, fuel costs and thermal efficiencies. Finally, he includes reliability statistics for each type of unit.

Load Description Program

This program translates forecasts of electric system demands into a set of load duration curves. These load duration curves serve to drive the model. Since the function of the capacity expansion model is to provide an optimal plan for meeting a specified demand, the analyst thus controls the outcome of the planning process by adjusting the specification. The load description program is the principal link between the economic development plan and the capacity expansion plan.

Expansion Configuration Generator Program

The planner exercises control on the outcome in this program by a) specifying reliability requirements, and b) by placing limits on the number of any expansion candidates which may be considered in a given year. The specification of reliability requirements determines the reserve capacity which the model plans.

Optimization Program

The analyst provides data of rate of return, escalation rate and penalty on foreign expenditures which are used in the economic calculations. The rate of return selected will have a strong influence not only on present worth estimates but will affect scheduling of project additions and choice of more capital intensive vs less capital intensive projects.

The influence of the analyst's judgement on the outcome of the expansion planning process is very strong indeed. The responsible decision maker must assure that judgements exercised by the analyst in including technical and economic data and system configuration constraints are reasonable and acceptable to policy makers. WASP assists in this process by indicating when the optimal plan is constrained by an "allowable" system configuration. The analyst then has the option of relaxing the constraint (permitting an otherwise unallowable configuration) and observing the effect on the optimal plan.

3. USES OF THE LOAD DURATION CURVE

We have already said that data of expected electric demand is entered into WASP in the form of seasonal load duration curves - up to four for each year in the planning period. In this section we shall review the derivation of the load duration curve from the variable load curve. We shall continue by demonstrating how the load duration curve becomes the key to the development of the system loading order, the estimation of the loss-of-load probability of the system and the evaluation of storage and innovative generating systems.

The horizontal axis of the load duration curve is in units of time typically hours. The vertical axis is in terms of load typically megawatts. A point on the curve is characterized by the number of hours (abscissa) that the load equals or exceeds a given magnitude (ordinate). A load duration curve indicating the significance of points on the curve is shown in Figure 2. A probabilistic interpretation may be given the load duration curve by defining the horizontal axis as a decimal fraction of the total period. The abscissa of a point on the curve then is the probability that the load will equal or exceed a magnitude given by the ordinate.

WASP combines the probability density distribution underlying the load duration curve interpreted as a cumulative probability distribution with the probability of failure (forced outage) of generating units to yield a loss-of-load probability. Loss-of-load probability refers to the probability that consumers will experience loss of service due to a failure of generators. Loss-of-load probability may be decreased in several ways: making generating units more reliable, increasing redundancy, in other words increasing reserve capacity, and for a given level of reserve capacity employing more small units rather than fewer large units.

To consider the role of the load duration curve in evaluating the effects of grid connected storage or innovative generation, we recall that the load duration curve is derived from the time varying load curve simply by summing all hours on the latter for which a given load is equaled or exceeded. Pumped storage for instance affects the system by imposing a pumping load at certain hours. At peak, when stored waters are released through turbines, the effect is to relieve load on the rest of the systems generation. Figure 3 shows the way in which pumped storage modifies the load duration. Wind energy or solar energy (insolation) used to generate electricity will if unaccompanied by storage have a random effect on reducing system demand. In order that WASP may be used when such sources are grid connected it is necessary that historical wind or insolation records be available so that estimate of the time magnitude of energy delivery may be made. Based on such records estimated electrical energy combinations may be used to modify load duration curves. On the other hand when wind and solar energy sources are used with storage the situation becomes much like that for pumped storage (Figure 3) except that pumping energy does not appear since it is from the solar or wind source.

In using WASP for the estimating of the "value" of solar or wind energy devices to the electric utility system the analyst would first optimize the expansion plan without the innovative source. The system is then optimized with the innovative source(s). The difference in the values of the objective function obtained will represent the "value" of the alternative energy source. It is understood that for each case the system reliability specifications must be met and where solar or wind energy sources do not have associated storage curve must be taken that no capacity value is assigned.
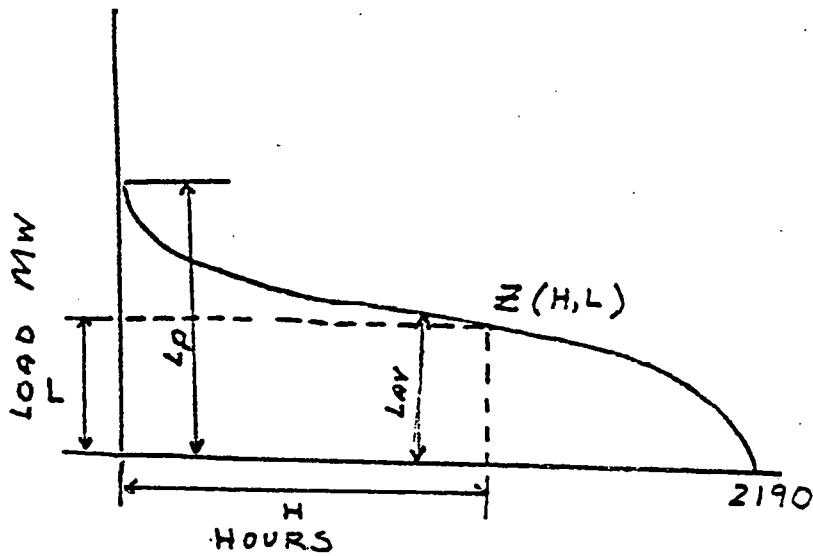
Point Z on the load duration signifies that for H hours in the season, the system load is equal to or greater than L.

The load factor $\frac{Lav}{Lp}$ where

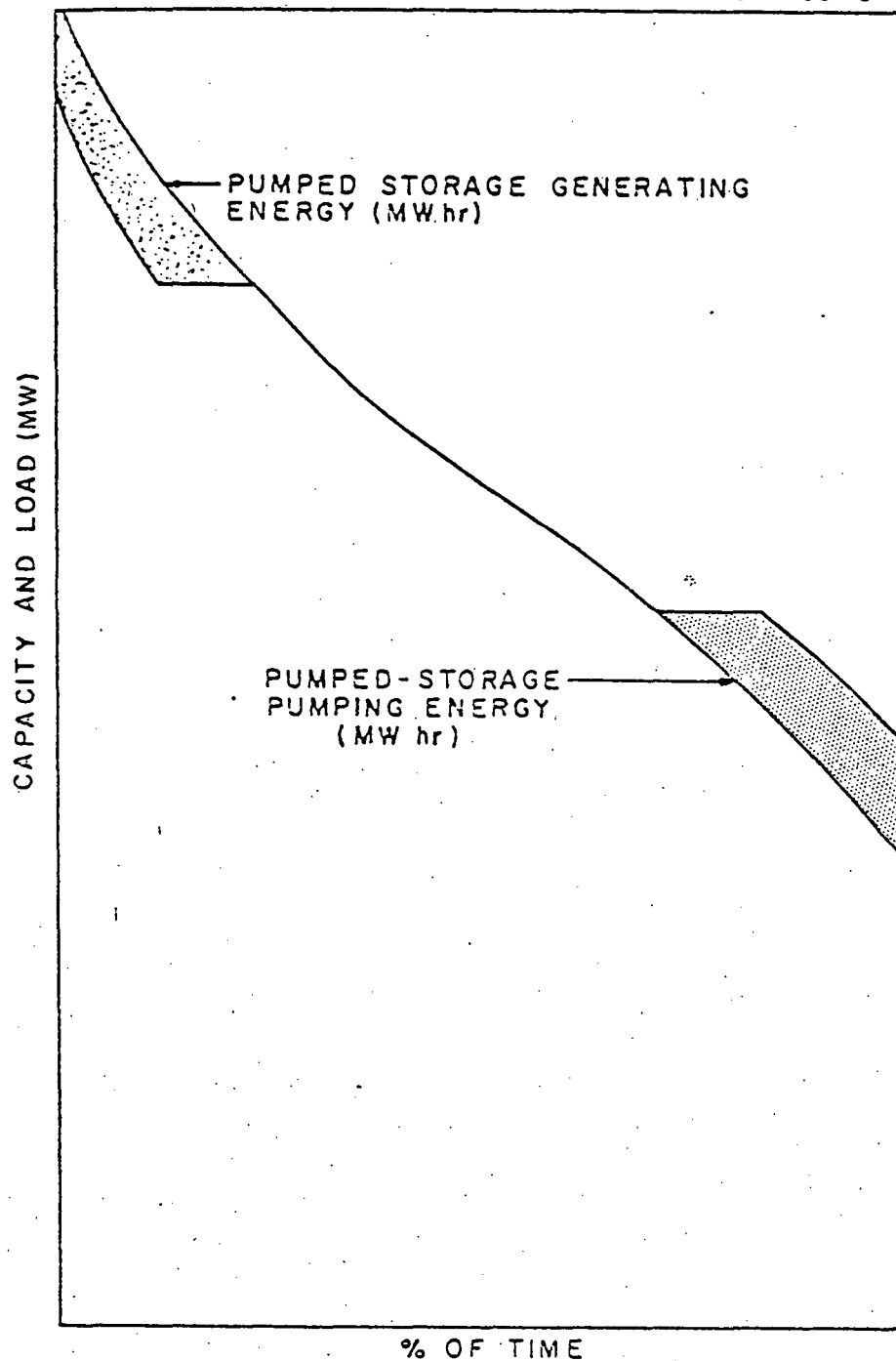Lav is the average load

Lp is the peak load.

Figure 2.

Figure 3.

4. EFFECTS OF KEY VARIABLES

Turning our attention once more to the requirements for the determination of the optimal expansion plan we will now review in qualitative terms the way in which uncertainties in key variables may affect capacity expansion decisions. These uncertainties may be resolved by the planner prior to the inclusion of the affected data in WASP or on the other hand he may wish to test the sensitivity of results to changes in these data.

Demand Uncertainties

Key to the estimation of the capacity requirements at any time was the forecasted load as described by the load duration curve. It was pointed out earlier that importance of accurate long range load forecasting is underscored by the fact that contractual commitments for base load generating capacity additions must be made as long as 7-10 years in advance of a commercial operation date. In addition to increased requirements for electricity which are the consequences of planned economic development, migration to urban areas where electricity is available, from the countryside where it is not, may effect peak loads as well. Realization of a peak load which falls short of the forecasted peak will result in the existence of excess capacity the costs of which must be carried by consumers. On the other hand an actual peak load which exceeds the forecasted load may result in a capacity shortage. It is frequently argued that the second effect is more serious than the first. The validity of such arguments can only be assessed in the context of a specific system and the estimated costs of service curtailments.

Supply Side Uncertainties

Capacity requirements are sensitive to the estimated forced outage rates of capacity additions. When these rates are underestimated capacity will be inadequate. There has been a tendency to use "immature" and "mature" forced outage rates. The first is usually applied to the first 2-3 years of operation on the assumption that during initial operation forced outage rates are greater. For generating units of the largest capacities or innovative design the validity of assuming a forced outage rate decreasing with time has not been established by experience. Similarly, estimated required maintenance time affects capacity requirements. When more maintenance time is required than has been forecasted, capacity may be inadequate. In the context of an underdeveloped economy it is likely that outage rates and maintenance time will be greater than in an industrialized country.

Fuel Costs

Forecasts of future costs for fossil and nuclear fuels are subject to large uncertainties. The fact that for fossil plants fuel accounts for some 80% of production costs is an indication of how sensitive the results of a present worth calculation of future variable costs is likely to be to "errors" in estimating fuel costs. Where a developing country has indigenous resources the valuation of such resources in domestic use is crucial to the technology selection process. Where petroleum is present for instance, should it be valued at the world-market price or at

extraction cost in choosing between oil based or nuclear based electricity generation? If the world market price is perceived as the correct value of domestically produced petroleum the technology choice is likely to be nuclear on straight-forward economic grounds. On the other hand, dependence on foreigners for nuclear fuel might mitigate against such a choice.

Rate of Discount

The rate of discount affects decisions as among technologies as well as in the timing of projects. A high discount rate is likely to cause postponing capital intensive projects, while a low rate will tend to make earlier capacity additions of this type appear more economical.

Valuation of Local Labor

The selection of the appropriate generation technology as well as the appropriate construction technology may be affected by the valuation of local labor. Questions as to the correct social wage arise where there is considerable underemployment or unemployment, a condition endemic to underdeveloped countries. Where such conditions exist capital intensive construction technology may be inappropriate. On the other hand generation technologies which are capital intensive may be favored. For instance hydro projects where dam construction may be economically undertaken using manual labor may be an appropriate choice where otherwise a fossil fired generating station would have been selected.

Construction Period

During the construction period, investment in the project underway is not earning revenues. Interest during construction is sensitive to the length of the construction period. The length of the construction period effects capacity expansion economics in other ways as well: a) cash requirements during construction are a function of the project schedule and b) the failure to bring capacity expansions to commercial operation on schedule may impose serious production limitations leading to failure in the realization of the development plan.

5. CANDIDATE EXPANSION PLANS AND SYSTEM OPERATION

The system planner is concerned not only with the economics of the expansion plan but its compatibility with system operation under fault conditions. The sudden loss of a large generating unit or the sudden imposition of a large block of load introduces a perceptible decrease in electric power system frequency which may seriously affect the system stability. The extent of the system disturbances should be limited to a 3% drop in frequency during the first 5-7 seconds after the transient occurs. There is no assurance that the optimal system as determined by WASP will meet operating criteria. WASP, however, does provide a program which computes the frequency drop which may arise from the sudden loss of the largest unit.

The magnitude of the frequency change due to the sudden loss of the largest generating unit is a complicated function of the fast spinning reserve, the system load prior to the disturbance and the size of the largest generator all expressed on a per unit (or fraction of peak load)

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basis. In addition the inertia of the rotating components of the system affects the frequency response. The frequency excursion is greater when the capacity of the generator which is lost is large relative to the system capacity. This effectively provides a technical limit to the maximum capacity of an individual generating unit which may be absorbed by a utility system of a given size. The fast spinning reserve capacity is the unused capacity of machines running and connected to the system.

Because of the technical constraint on the capacity of the largest unit on the system described in the foregoing paragraphs it is necessary that considerate expansion plans be characterized in sufficient detail to establish whether or not the expanded system meets the criterion stated above for maximum frequency change as a consequency of a disturbance. This data requirements are summarized in Figure 4.

This limit on the size of the largest unit, typically 15% of the peak load on the system, turns out to have consequences for non-economic policy as well, specifically the question of "going nuclear". Nuclear generating units available from vendors in the industrialized countries have a minimum rating of 600 Mw. This implies that for systems having a peak load less than 4000 Mw such units are inappropriate for purely technical reasons. (As a point of reference the Consolidated Edison Company of New York peak load in 1976 was 7600 Mw). India is building 220 Mw nuclear units for domestic use. The availability of units of this size would reduce the minimum peak level for which nuclear units would become technically appropriate to approximately 1500 Mw. The minimum system size refers to the size of the integrated system of which the nuclear power plant is to be a component and <u>not</u> to the size of the national load. This fact is important in countries where there are two or more grids either independent or weakly connected.

5. ENVIRONMENTAL CONSIDERATION

Within WASP there is no explicit consideration of environmental constraints. In the paragraphs which follow we outline an approach[2] to such consideration which is compatible with WASP.

Environmental considerations are likely to affect both fixed and variable cost components. An example of the former is the installation of scrubbers in fossil power plants, which increases the investment requirements per unit of capacity. An additional effect of scrubber installation is likely to be an increased forced outage rate which on a system wide basis implies additional capital costs for reserve capacity. Limitation of the temperature of a natural heat sink to some environmentally permissible level imposes additional operating costs.

In this "cost adder"[2] approach environmental goals are specified. These goals may address a single environmental consideration, again for example, the temperature rise in a natural body of water used as a heat sink as an example. In this case each goal is characterized by a different temperature rise. On the other hand goals may be characterized by consideration of a set of environmental concerns setting a specific goal for each. For each alternative capacity expansion plan a set of designs

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System Frequency Response To Loss Of Generation

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                          ┌─────────────────────────────────┐
                          │   Technical Characterization    │
                          │           Including             │
                          ├─────────────────────────────────┤
┌──────────────────┐      │                                 │
│ Existing System  │──────│   System Inertia Constant       │
└──────────────────┘      │                                 │
                          │   Reheat Thermal Plant Steam    │
                          │                                 │
                          │   Valve Time and Time Constant  │
                          │                                 │
┌──────────────────┐      │                                 │
│Candidate Expansion│─────│   Hydro Plant Speed Governor    │
│      Plan         │     │      Droop                      │
└──────────────────┘      │                                 │              ┌──────────────┐
                          │   Water Starting Time In        │──────────────│  Frequency   │
                          │      Hydro Intake               │              │    Drop      │
                          │                                 │              └──────────────┘
                          │   Load Served Before Loss       │
                          │      of Generation              │
┌──────────────────┐      │                                 │
│ Forecasted System│──────│   Fast Spinning Reserve         │
│      Loads       │      │      (Max)                      │
└──────────────────┘      │                                 │
                          │   Other                         │
                          └─────────────────────────────────┘
```
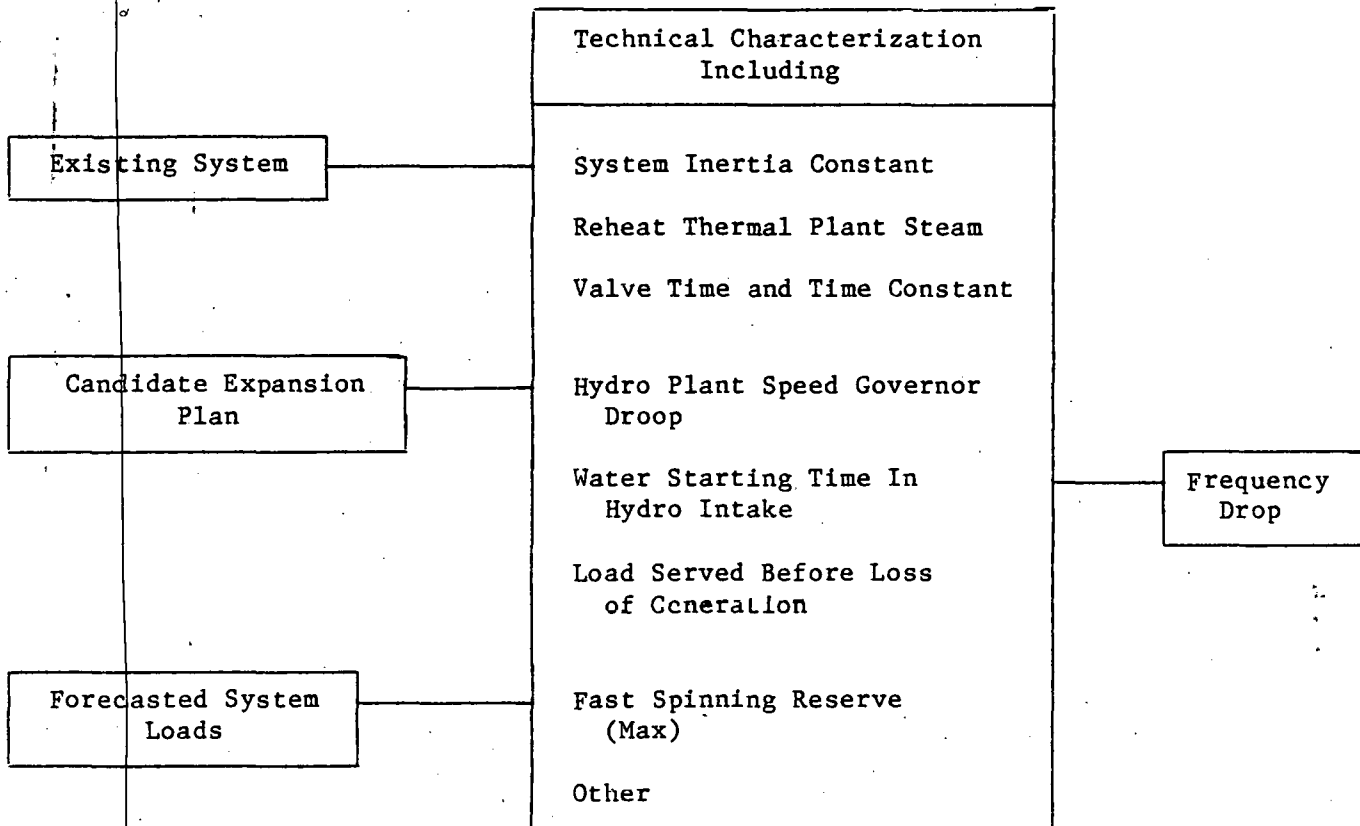
Figure 4.

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meeting each set of environmental specifications must be prepared and associated capital and operating "cost adders" estimated. These cost adders are then included in the estimation of costs associated with each expansion candidate. A ranking by cost of each alternative plan is established as before. A selection is then made on the basis of a minimum discounted cost for a given set of environmental goals.

7. SUMMARY

We have attempted in this short paper to describe how to review how key economic and technical factors enter the electric capacity expansion planning problem in the context of underdevelopment. We have examined this problem in the context of WASP and have cautioned users as to the importance of assumptions on the part of the analyst in the model's output. These include in addition to the allowable configuration which the generating system may take considerations of system reliability the valuation of local labor, indigenous resources, independance of energy resources and the rate of discount. A suggestion as to the inclusion of environmental factors was also made.

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