Expansion Planning for Electric Power Systems

by A.J. Covarrubias

INTRODUCTION

Electricity is so basic to the world economy that certain electricity indices are used to express a country's economic standing (consumption or production of electricity per capita) and the standard of living enjoyed by a people (per capita electricity consumption in the domestic sector). Moreover, electricity supply has special characteristics which make the service unique as compared to other types of industry. The end product has to be delivered instantaneously and automatically upon the consumer's demand; except for pumped storage plants and electric batteries, technologies do not exist that can produce it economically at uniform rates, hold it in storage in large quantities, and deliver it under convenient schedules; insufficient capacity (shortage) or excessive capacity (idle capacity) have negative effects on the economy; the close inter-relation with economic and social factors imposes labour, environmental, financial and other constraints on the problem. Careful planning of the electric sector is therefore of great importance since the decisions to be taken involve the commitment of large resources, with potentially serious economic risks for the electrical utility and the economy as a whole.

POWER SYSTEM PLANNING

Power system planning is part of a more general problem, that of energy and economic development planning. Its objective is therefore to determine a minimum cost strategy for long-range expansion of the generation, transmission and distribution systems adequate to supply the load forecast within a set of technical, economic and political constraints.

Traditionally, power system planning has been mainly related to generation expansion planning. This is due mainly to the fact that investment in transmission lines is a relatively small fraction of the investment in the construction of power stations and that investment in the distribution of electric energy to customers, although sizeable, is to a large extent independent of the generation and transmission system.

The main steps in power system planning may be summarized as follows:

(a) Study of the electric load forecast 5 to 30 years into the future, based on the most reliable information.

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(b) Evaluation of the energy resources available in the future for electricity generation and the foreseeable trends in technical and economic developments.

(c) Evaluation of the economic and technical characteristics of the existing system of generating units and of the plants that are considered as potential units for system expansion. These characteristics include capital investment cost, fuel cost, operation and maintenance costs, efficiencies, construction times, etc.

(d) Determination of technical and cost characteristics of the plants available for expansion.

(e) Determination of the economic and technical parameters affecting decisions such as discount rate, level or reliability required from the generating system, etc.

(f) Choice of a procedure to determine the optimal expansion strategy within the imposed constraints.

(g) Qualitative review of the results to estimate the viability of the proposed solution.

The determination of most of these data must take into account the present and future economic and technical environment within which the electric sector is expected to operate. Thus, available resources and fuel prices are related to the energy policy of the country; economic development policies, existing and foreseeable, should be considered in the demand forecast, interest and escalation rates are also dependent on the economy; acceptable system reliability should be future-oriented

Because of the many variables involved in electric system expansion problems, many mathematical models have been developed by planners in order to tackle the problem in a systematic way. Refs.[1], [2].

THE WASP PROGRAMME FOR GENERATING SYSTEM EXPANSION PLANNING

During the past several years, the IAEA has assisted numerous developing Member States in carrying out electric power system planning studies using a computer programme called WASP (Wien Automatic System Planning Package) Ref. [3]. This programme provides a way of estimating the most economic schedule for adding new generating capacity to an electric power system over the medium and long term It is the second generation of an earlier power system planning programme developed by and for the Tennessee Valley Authority in the USA. The package is designed to find the "optimum" power system expansion plan within established constraints. By "optimum" is meant that the discounted cash flow (capital and operating expenses) is minimized over a given period with provision made to reduce the effects of uncertainties beyond that period. This is carried out using the dynamic programming approach. Dynamic programming, in its most general sense, is an ideal method for solving the system planning problem. However, even with a limited range of possible expansion plans, this approach is impractical without the aid of a computer. With the additional range of generating units now available, the number of possible expansion plans is so large that even with the aid of computers general dynamic programming is impractical.

The WASP package represents a compromise The system planner can direct the area of study to configurations which he believes most economic, but the programme will tell him if his restrictions are a constraint on the solution. WASP then permits him to modify his constraints and, without repeating all the previous computational effort, to determine the effect of the modification. This process can be repeated until an optimum path conforming to the user-imposed constraints is determined.

The WASP package consists of the following seven modular programmes:

1. A programme to describe the forecast peak loads and load duration curves for the system (LOADSY).
2. A programme to describe the existing power system and all future additions and retirements which are firmly scheduled (FIXSYS).
3. A programme to describe the candidate plants which might be used to expand the power system (VARSYS).
4. A programme to generate alternative expansion configurations (CONGEN).
5. A programme to determine whether a particular configuration has been simulated and, if not, to simulate operation with that configuration (MERSIM).
6. A programme to determine the optimum schedule for adding new units to the system over the time period of interest (DYNPRO).
7. A programme to summarize the imput data, results of the study and the cash flow requirements of the optimum solution (REPROBAT).

Each of the first three programmes creates data files which are used in the calculations. Additional files are created by the fourth and fifth programme and are used in the sixth. Each programme produces a printed summary. The seventh programme provides a report of the study.

An immediate advantage of the modular programme approach is that the first three programmes can be run separately to eliminate the bulk of the data errors. These programmes are very fast to run, thus avoiding extensive long runs with incorrect data. The separation of the programme generating expansion configurations from that doing the simulation produces further savings in computer time since those expansion configurations that may have involved data errors in the generating programme can be eliminated from the simulation. The ability to save simulation results on a data file is the major time-saving feature of the programme. While searching through a successive re-run of the last three programmes for the unconstrained optimum, only those simulations which have not been performed are executed. Since simulation is the most time-consuming part of examining an expansion configuration, the computation time saved can be very large.

A second advantage of the modular concept is that the amount of memory required at any time can be minimized, allowing the use of relatively small computers. This is of particular importance when considering that the IAEA assistance to its Member States contemplates the transfer of the WASP methodology.

An interesting feature of the programme is that reliability and generating costs of the system's annual configurations are estimated using probabilistic methods. Hence, stochastic variables such as the availability of water for hydroelectric generation and unavailability, planned or unplanned, of thermal generating plants receive a probabilistic treatment. The results of the programme have thus removed uncertainties about the influence of these stochastic variables on the optimal expansion plan.

In this respect, the unavailability of thermal generating units is represented by the scheduled maintenance requirements (planned outages) and the forced outage rate (unplanned outages). In the case of hydro, the user can specify as many periods in the year (seasons) as required to represent the availability of water. Moreover, it is also possible to specify up to five different hydro conditions, i.e. extremely dry year, dry year, normal year, wet year, very wet year, along with the probability of occurrence of each condition. This is very important with systems with a large component of hydro energy with varying hydrology.

Within the memory limitations, WASP can consider up to:

- 30 years in the study period, each year sub-divided into periods (1–12).
- 5 sets of hydrological conditions.
- 100 multi-unit plants in the existing system, with normal hydro, emergency hydro and pumped storage, if any, each treated as a single, composite plant. This limit of 100 must be reduced, however, by the number of expansion candidate plant types (see below).
- 20 expansion candidate plant types. In addition to thermal units, hydro and pumped storage units can be included in the list of alternatives. If a series of hydro or pumped storage projects is to be considered by the programme, projects of each type must be identified in the chronological order in which they could be installed in the system. Up to 20 such projects may be included in the list. When hydro or pumped storage units are added to the system, they are merged with the existing hydro or pumped storage units. Therefore, all of the hydro projects count as only one alternative plant and all of the pumped storage projects count as an additional alternative plant.
- 200 alternative system configurations per year, with a limit of 2000 configurations for the study period in a single computer run.

The computer time required to carry out a planning study will depend on the complexity of the system being simulated, on the number of hydrological conditions considered, on the number of years included in the study period, on the number of periods into which the year is divided, on the total of configurations generated at each iteration, and finally on the simulation accuracy desired. The present version of WASP-II includes some routines written in ASSEMBLER language to reduce computer time requirements.

ECONOMIC MODEL OF THE WASP PROGRAMME

The purpose of an electric power system planning study is to determine the optimal pattern of system expansion to meet the electric energy requirements of a country over a given period. Nuclear power planning studies, such as the ones carried out by the IAEA at the request of various Member States Refs. [4], [5], [6], [7], [8], [9], are performed with a similar aim but with particular emphasis on estimating the possible participation of nuclear power in the optimal pattern of expansion. Ideally, the performance of this task would require estimating and comparing benefits and costs, both direct and indirect, arising from alternative development patterns, in order to determine the power expansion plan yielding maximum total net benefits. Because of time limitations, a series of simplifying assumptions are unavoidable. The methodology used by WASP represents an attempt at achieving a compromise between practical constraints and theoretical consistency.

The main components of this methodology involve:

(a) A definition of costs and benefits to be considered and the development of methods for estimating their quantitative values.

(b) A selection of criteria for comparing benefit and cost streams extending over time and containing domestic and foreign currency components in variable proportions.

It is assumed that costs rather than net benefits are the only yardstick. This is tantamount to assuming that all programmes of electric power expansion meeting projected demand with the imposed constraints on reliability offer the same total benefits and that the least-cost programme is consequently the most advantageous for the ultimate consumers. In comparing alternative ways of producing the same commodity, in this case electric power, this is a less questionable alternative than it would be in the general case of comparing alternative projects with different outputs. It does, however, ignore such indirect effects as, for instance (1) different employment levels arising from different power programmes and the consequent effects on savings and investment and (2) the future value of acquiring a pool of labour skilled in constructing and operating nuclear stations.

Only costs directly connected with electricity production through a particular type of plant are taken into account. In particular, such external costs as those arising from increasing environmental pollution in the case of fossil-fuelled stations or from the relatively larger thermal pollution by nuclear stations are disregarded in the basic analysis. The imposition of strict environmental controls by industrial countries leading to higher capital and fuel costs for thermal power stations shows that "external" costs may easily become "internal" over time.

In all cases costs are defined as costs to the economy rather than costs to the electricity producers. A major consequence of this criterion is to eliminate taxes on all types of fuel and equipment from all cost inputs. This is a particularly critical assumption in the case of countries imposing a heavy fiscal burden on some types of fuel and in particular on fuel oil. Since the countries concerned are the best judges of their tax policies, which may involve items of social benefit disregarded by the study, and since the electric utilities certainly view taxes on fuel and equipment as elements of costs, alternative computations treating taxes as elements of costs can be carried out for cases which are expected to show critical differences in results.

The aggregation of domestic and foreign currency costs is carried out on the basis of the official rates of exchange prevailing at the time the study is undertaken. It is recognized that for many countries the official exchange rates are somewhat arbitrary and do not take full account of the supply of and the demand for foreign capital. Evidence for this is the existence of foreign exchange rationing and control, and parallel markets. Although this approach may substantially underestimate the true value of the ratio of foreign to domestic costs, alternative assumptions would have comparable uncertainties.

As to the selection of the currency serving as common denominator, the US dollar was chosen for purposes of convenience and not because of any particular expectations of stability.

The aggregation and comparison of time flows of costs is done through a discounting of their present worth values at a rate that is assumed to remain constant in time. This principle implies two decisions:

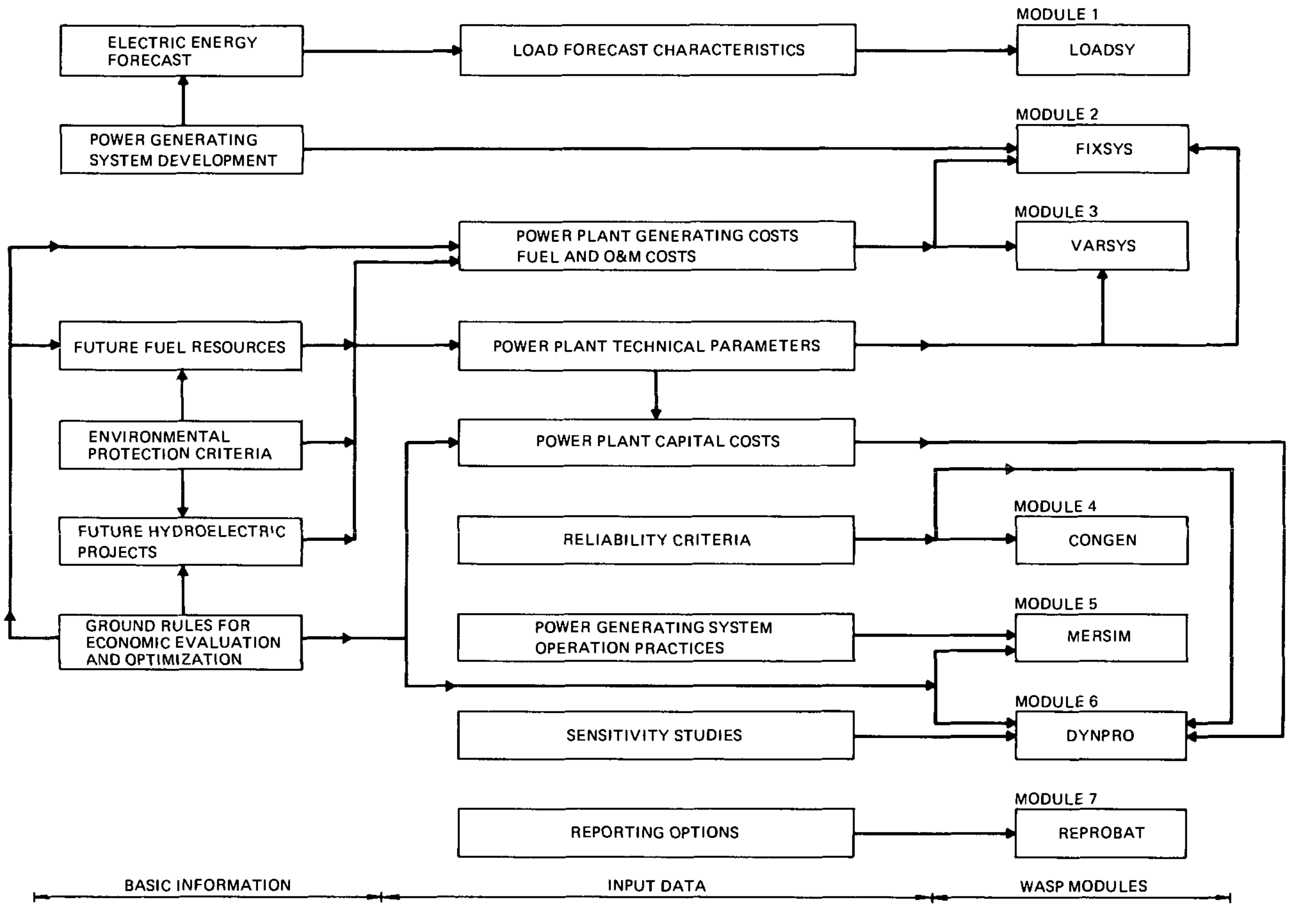

Figure 1. WASP Input Data Model.

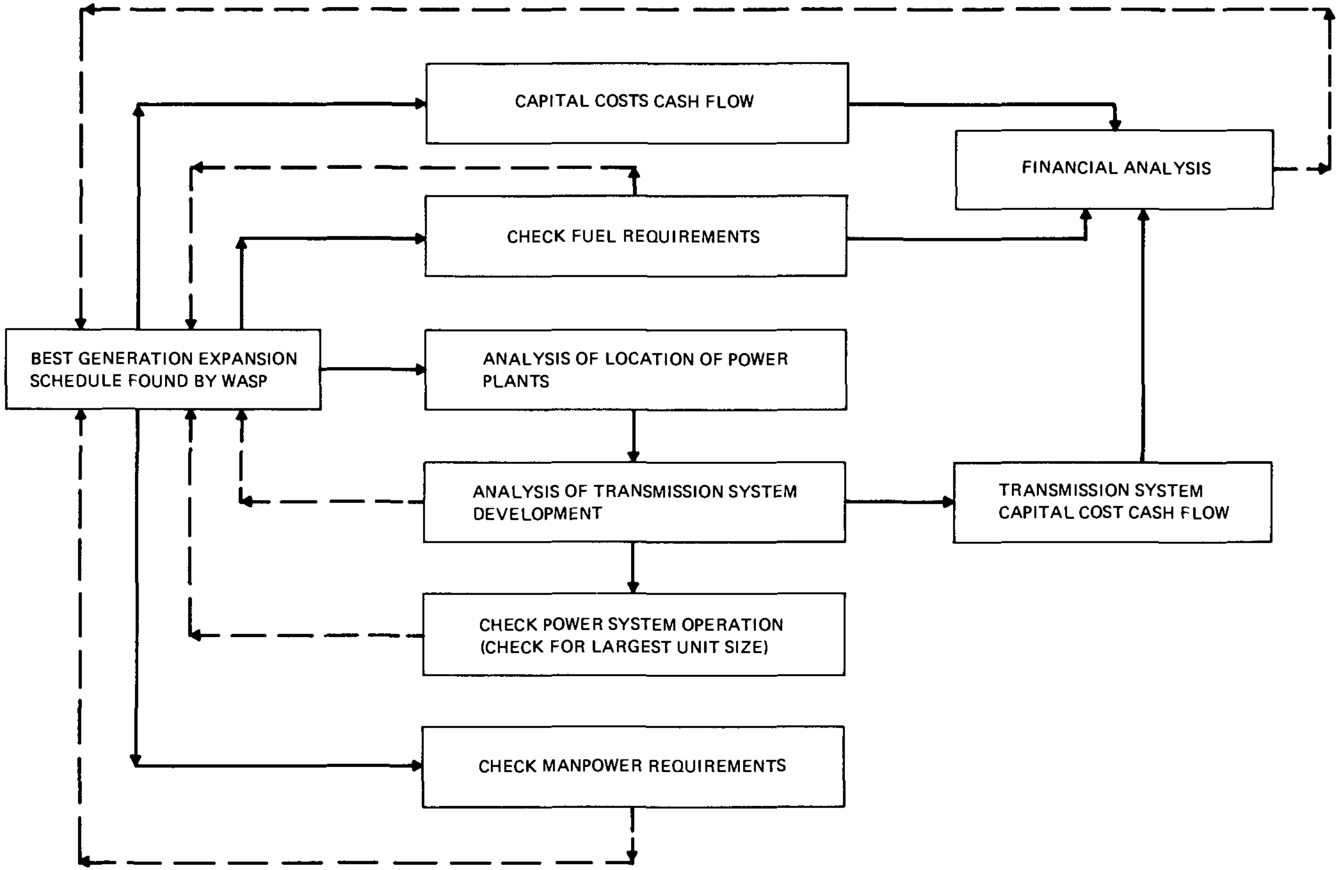

Figure 2. Analysis of WASP Output.

(a) The selection of present worth as a criterion. This decision must be assessed against its possible alternative, which would be to rank different patterns by their internal rate of return. The latter is, however, clearly ruled out since, apart from its theoretical flaws in the comparison of mutually exclusive projects, it requires estimates of benefits which the study refrains from making.

(b) The assumption that the rate of discount remains constant in time may be open to objections since its value should in principle slowly decrease with higher levels of economic development and larger stocks of capital equipment. It is felt, however, that the practical difficulties involved in estimating and in using variable rates of discount far outweigh the possible advantages.

Finally, the rates of discount and of inflation are combined into a single equivalent rate of discount. This considerably simplifies the computational work since it is then possible to proceed on the basis of constant prices.

The steps involved in a power system expansion study using the WASP package are shown schematically in Figures 1 and 2. Briefly, these are as follows:

1. Correlate historical data which might be used to forecast the future demand for electricity.
2. Select a forecast of peak demand to be used as the basis for the study and define the shape of the load duration curves.
3. Define the characteristics of the plants in existence or committed for the electric power system being considered.
4. Define the characteristics of generating plants which might be considered as expansion alternatives.
5. Evaluate the role of indigenous energy sources such as coal, gas and hydro.
6. Define the economic data and parameters to be used.
7. Determine the approximate size of the largest generating unit that the system can accept from the standpoint of frequency stability and transmission line considerations.
8. Determine the optimum (minimum cost) expansion programme.
9. Determine the sensitivity of the results to variations in the economic data.
10. Estimate the financing requirements for a selected power expansion programme.
11. Check for transmission system and operational constraints.
12. Check for financial constraints.
13. Check for other constraints, i.e. construction capabilities, etc.

ADVANTAGES OF THE WASP ECONOMIC MODEL

The traditional method of comparing the economics of nuclear and conventional plants has been to calculate generating costs for each type of plant using suitable capital, operating, and fuel cost data along with an assumed plant load factor and cost of money. This approach was adequate until recent years because the choice of generating equipment available to an electric utility was fairly limited. In many cases one had only to compare nuclear and conventional fuel-fired units of a given size, the size being selected intuitively depending on the size of the system. Hand calculations were usually adequate for such an approach.

The above-mentioned method of power system planning now appears to be inadequate for a number of reasons. First, the choice of generating units is much wider and includes gas turbines, hydro plants, pumped storage plants, various types of fossil-fired units and even various types of nuclear plants. Second, because of the very large investments involved, the choice of optimum size of unit becomes quite importent. Third, the position of a plant in the loading order influences its capacity factors and comparisons of alternatives using the same capacity factors may not be valid. Finally, because of the high costs of fossil fuels, particularly imported gas and oil, it is necessary from an economic standpoint to minimize total system costs taking into consideration not only existing plants but also plants which might be added over the longer term. The use of WASP permits one to take all of these factors into consideration. Another advantage of using WASP stems from the probabilistic treatment of hydro generation and of the availability of thermal power plants, thus removing the uncertainties inherent in those models that consider a deterministic approach for these random variables.

RELEASE OF THE WASP PROGRAMME TO IAEA MEMBER STATES

The Agency has transferred the WASP programme to 38 countries who had agreed to certain conditions for the release and to 5 international organizations. A total of 16 countries have applied to the Agency for training in the WASP methodology during the period 1974 to 1977 and, as a result, 34 engineers were trained in Vienna for varying periods of time. The need in many Member States for further specialized training in electric system expansion planning using the WASP programme led the Agency to sponsor a series of training courses on that subject. Two such training courses were held at the Argonne National Laboratory in the USA, for a period of nine weeks at the beginning of

Figure 3. The WASP training course held from February 14 to April 14, 1978 at Argonne, USA, drew 16 participants from five countries. They are pictured here with the course organisers and lecturers.

1978 and 1979, attended by a total of 40 participants from 18 countries. Due to the success of theses courses, further training courses on electric system expansion planning using the WASP methodology are foreseen in the years to come.

References

[1] Dennis Anderson, "Models for determining least-cost investment in electricity supply", The Bell Journal of Economics and Management Science, Vol 3, No. 1, Spring 1972

[2] H Balériaux, E. Jamoulle, F Linard de Guertechin, "Simulation de l'exploitation d'un parc de machines thermiques de production d'électricité couplé à des stations de pompage", Review E, Suppl. Bull. Soc. Belge Electr 5, 7, 1967, 3.

[3] R.T Jenkins, D.S Joy, "Wien Automatic System Planning Package (WASP) — An Electric Utility Optimal Generation Expansion Planning Computer Code", USAEC Report, ORNL-4945, July 1974.

[4] IAEA, "Market Survey for Nuclear Power in Developing Countries — General Report", Vienna, 1973

[5] IAEA, "Nuclear Power Planning Study for Indonesia", Vienna, 1976

[6] IAEA, "Nuclear Power Planning Study for Bangladesh", Vienna, 1976

[7] IAEA, "Nuclear Power Planning Study for Pakistan", Vienna, 1976.

[8] IAEA, "Nuclear Power Planning Study for Hong Kong", Vienna, 1977

[9] IAEA, "Nuclear Power Planning Study for Venezuela", Vienna, 1978.